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REFERENCE

Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C., 35c.)

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American Journal of Science

JUNE 1953

SHEARS OF THE SECOND ORDER

H. E. MCKINSTRY

ABSTRACT. During movement on a fault plane, the stress orientation in the rock adjoining the fault is such that one plane of maximum shearing stress makes an angle with the fault plane approximately equivalent to 45 degrees minus the angle of friction, ø, for the fault surface. A second plane of maximum shearing stress is, of course, at right angles to the first. Shears formed in response to this stress orientation ("shears of the second order") would make angles of roughly $45° - \frac{ø}{2}$ and $135° - \frac{3ø}{2}$ with the fault. On the first of these, displacement is in the same sense as that on the fault; on the second it is opposite in sense.

THE PROBLEM

IN some districts an analysis of the pattern of fractures (including faults, joints and fissure veins) discloses two sets intersecting at an acute angle. The usual tendency of the structural geologist is to interpret them either as conjugate (complementary) shears or as a shear direction and a tension direction respectively. Geometry alone does not tell which, if either, of these interpretations is correct; additional evidence, either from the physical nature of the fractures themselves or from the sense of the displacement along them (or alternatively the lack of displacement) may provide a satisfactory solution. Thus if the displacement along one set is right-hand[1] and the other left-hand, the interpretation as complementary shears is plausible, providing the two sets are essentially contemporaneous.

If, however, the displacement on both sets has the same sense, i.e., both right-hand or both left-hand, they cannot be interpreted as complementary shears. Recourses, such as the assumption that one set is older than the other or that one

[1] Right-hand and left-hand, although less impressive than the equivalent terms dextral and sinistral, have a century or two of priority, at least among mining men.

set is influenced by pre-existing planes of weakness may be correct in certain instances, but these are not the only possible interpretations. It will be shown that if movement is in progress on a main fault or "master shear," stresses in the rock adjoining it will have such orientation as to cause failure on a new pair of mutually complementary planes, one of which will make an acute angle with the master shear. Shears of this type were described by Willis (1923, p. 176). That his explanation is difficult to reconcile with the theory of elasticity may explain why such shears have received little attention from structural geologists.

A shear of this type, which may be termed a *shear of the second order*, has such an attitude that the acute angle which it makes with the master shear points in the direction of displacement, that is, in the direction in which its own wall of the master shear was moving (fig. 1A).

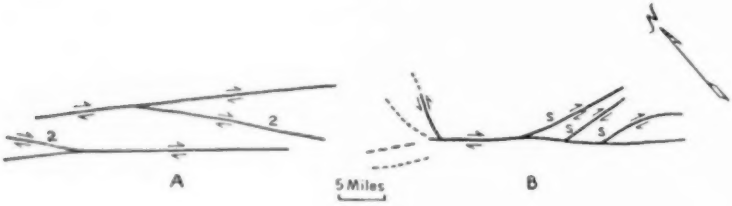


Fig. 1.

A. Shears of the second order (2) Yellowknife District, N.W.T. (after Ira Brown).

B. Splay faults, (s). Craven fault system, Ross-shire (after Anderson).

As Willis points out (1923, p. 64), such shears are to be distinguished from the faults involved in *schuppen* or imbricate structure, whose acute angle with the main fault, or sole, points backward with respect to the direction of movement. Similarly they are to be distinguished from the splay faults described by Anderson (1942, p. 88) (fig. 1B).

As the complement to a shear of the second order, there should, in theory, be another shear direction roughly at right angles to it. Such a "*complementary shear of the second order*" is not always developed, or if it is, it is hard to distinguish from the complement of the master shear, since the two would have similar sense of displacement.

EXAMPLES

Three examples on contrasting scales will suffice to illustrate fault patterns containing shears of the second order.

In the Yellowknife District, Northwest Territories, Henderson and Brown (1949) have mapped a pattern of faults in ad-

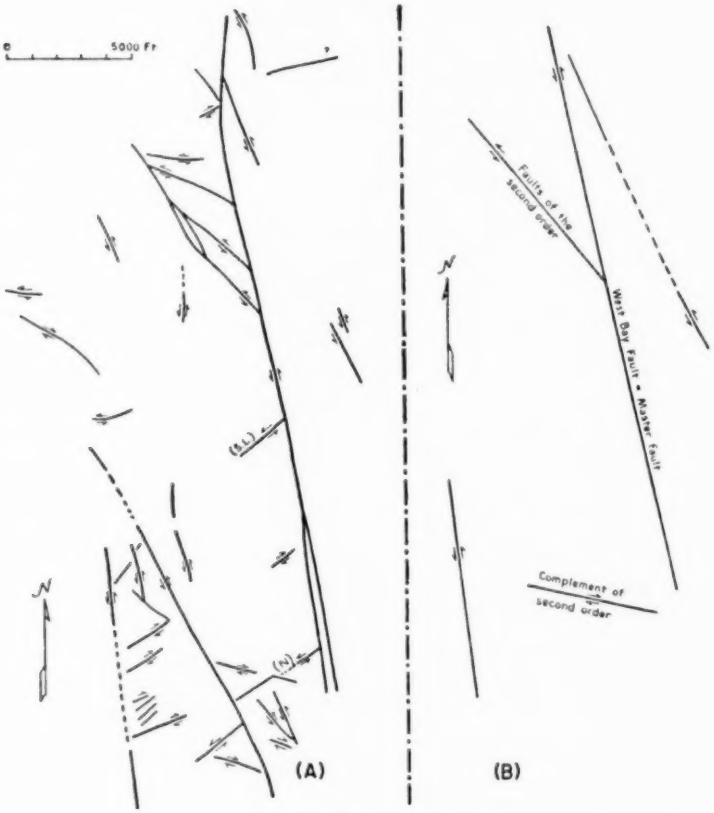


Fig. 2.
A. Part of fault pattern, Yellowknife District, N.W.T. (after Henderson and Brown).
B. Idealized pattern in Yellowknife District.

mirable detail (fig. 2A). The master fault, the West Bay fault, is essentially strike-slip. Its horizontal component of displacement is 16,000 feet while its vertical component is about 1600 feet (Campbell, 1948, p. 256). The attitudes of three sets of

faults (interpreted here as master faults and faults of the second order with their complements) are shown diagrammatically in figure 2B.[2]

In the Darwin Hills, California (fig. 3), Wilson (1943) describes a fracture system consisting of northwesterly tear faults, which have "a considerable component of dip displacement in addition to horizontal motion." The horizontal com-

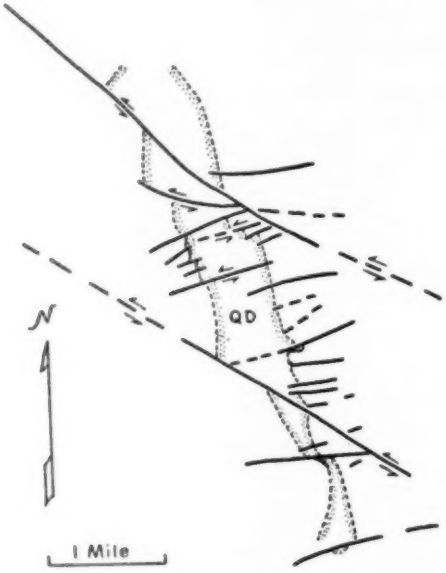


Fig. 3. Northeast striking fractures between northwest striking tear faults. Both sets have left-hand displacement (after L. Kenneth Wilson). Econ. Geology.

ponent of displacement is left-hand. Between the tear faults are northeasterly fractures which also show left-hand displacement. These northeasterly fractures carry scheelite orebodies and are described as tension fractures. While they may well have been opened by tensile stress at some stage, the component of horizontal displacement (left-hand) is well in-

[2] Two faults, the Negus (N) and the Sand Lake (S.L.) are incompatible with the mechanics of this system. Both are along lava-flow contacts and both are cut by the West Bay fault and by the faults of the second order. Apparently they belong to an earlier period of deformation.

dicated by offsetting of an igneous contact and of steeply dipping limestone beds.

On a smaller scale, a fault of similar orientation is figured by Wisser (1942, p. 233) in the Pachuca District, Mexico (fig. 4).

SLAB BETWEEN MOVING FAULTS

To visualize the mechanical origin of shears of the second order, one may first picture a mass of rock under compressive load[3] P and free to expand in one direction at right angles to P. Failure, if it takes place by shear, will occur parallel

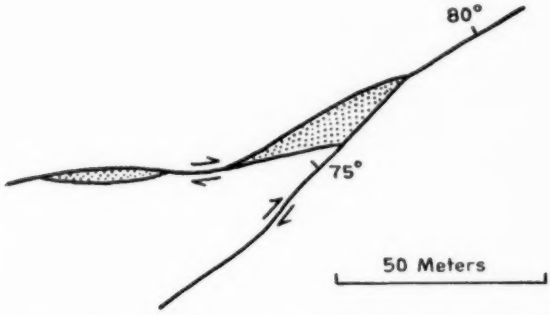


Fig. 4. Plan of a vein in the Northern Pachuca Area (after Wisser).

to either or both of two planes making equal angles with P. While failure parallel to either plane is equally possible, the initial failures often parallel one rather than both of the two possible directions. Before failure occurs the stress acting on any plane destined to become a fault has two components, one normal and one parallel to this plane (fig. 5A). Let us now assume that movement is in progress on two parallel planes and then center attention on the slab of rock between them (fig. 5B). For simplicity, let us imagine, for the moment, that the fault planes are perfectly lubricated, that is, movement takes place on them without friction. In this case the normal component of stress is transmitted in toto across the fault planes and continues to compress the intervening slab. The parallel component, however, cannot affect the

[3] Load is used here in the engineering sense and is not limited to gravitative load. In strike-slip faults, the force of gravity is not directly involved.

intervening slab in the absence of friction. It is now expressed by the force that accelerates fault-movement. Within the slab, therefore, the axis of principal compressive stress will be normal to the bounding faults. The planes of maximum shearing stress will stand at 45 degrees to it as well as to the fault planes.

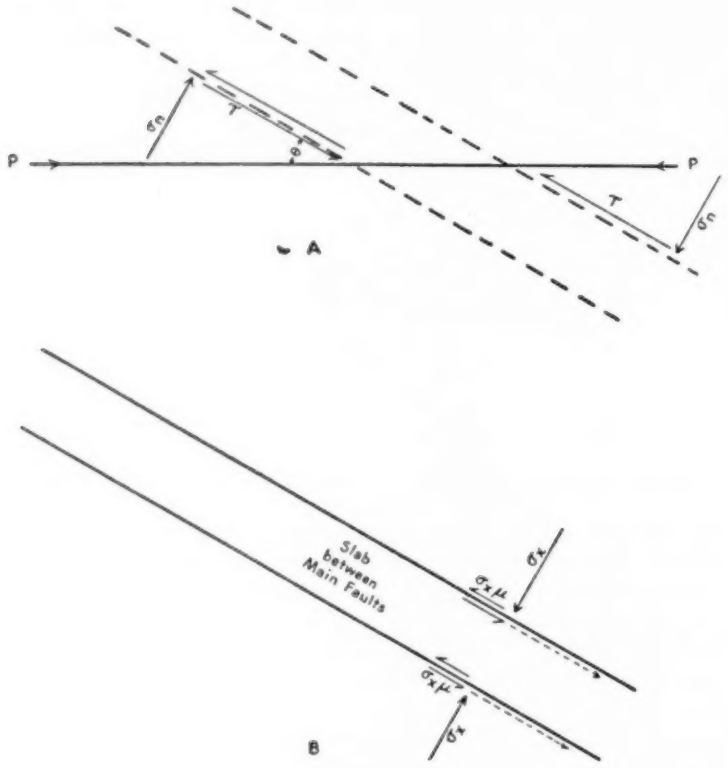


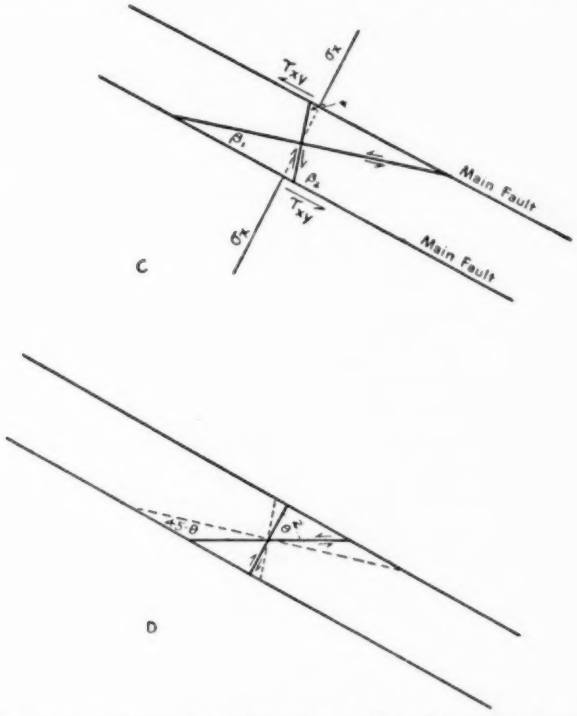
Fig. 5.
A. Components of stress on planes destined to become faults.
B. Stress orientation during fault movement.

INFLUENCE OF FRICTION

The assumption of a frictionless fault plane, however, is an over-simplification; actually movement on the fault plane will be partially resisted by friction and the friction will exert shearing stress on the rock within the slab. This stress will

be less than the corresponding shearing stress that existed before fault-failure began because part of the parallel component of force is now being expended in accelerating the fault-movement (fig. 6).

If the component of stress normal to the fault plane be denoted by σ_x and the coefficient of friction by μ (fig. 5B), then the shearing component due to friction will be $\sigma_x\mu$ (fig.



C. Planes of maximum shearing stress within slab during movement.
D. Planes of shear failure (solid lines with arrows) within slab.

5B). Under these stress conditions, the planes of maximum shearing stress will be determined by the equation:

$$\tan 2\,a = +\frac{\sigma_n}{2\,\tau} = +\frac{\sigma_x}{2\,\sigma_x\,\mu} = +\frac{1}{2\,\mu}$$

where:

a is the angle between the plane of maximum shearing stress and a normal to the fault plane and

τ is the shearing stress (in this case equal to friction).

If the angle of friction, ϕ is introduced, $\mu = \tan \phi$ and

$$\tan 2\alpha = \frac{1}{2 \tan \phi}$$

Now as a rough approximation, tan 2ϕ can be taken as equivalent to 2 tan ϕ (for example, for an angle of friction of 15 degrees the inaccuracy introduced by this assumption is about $1\frac{1}{2}$ degrees; for 30 degrees, the error is about $5\frac{1}{2}$ degrees). Then

$$\tan 2\alpha = \frac{1}{\tan 2\phi} = \operatorname{Cot} 2\phi = \tan (90 - 2\phi)$$

$$2\alpha = \pm 90 - 2\phi$$

$$\alpha = \pm 45 - \phi$$

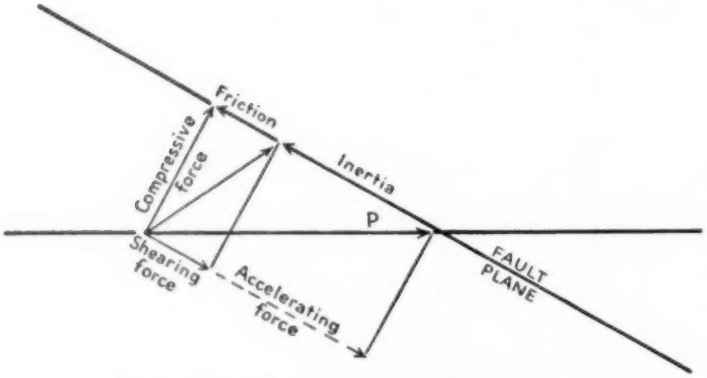


Fig. 6. Balance of forces during fault movement.

This equation gives the angle α between the planes of maximum shearing stress and a normal to the fault. Of more direct application is the angle β between the planes of maximum shearing stress and the fault plane itself.

If we add 90 degrees to the angles α, $\beta_1 = 90° - (45 + \phi) = 45° - \phi$ and $\beta_2 = 90° + (45° - \phi) = 135° - \phi$. These are the angles between the main fault and the planes of maximum shearing stress within the slab.

LOAD-COMPONENTS OTHER THAN P

The assumption so far has been that the faulting was caused by a simple compressive load, P. If, as in the more

natural case, there is a second component of loading, Q, at right angles to P, it will not alter the orientation of planes of maximum shearing stress within the slab. The normal stress, $\sigma_x = P\sin^2\theta + Q\cos^2\theta$, (where θ is the angle between P and the fault plane) and σ_x cancels out as before.

The geometry will not be different in principle if, as in the most general case, three mutually perpendicular components of load are all finite. In this case the letters P and Q may be assigned to the maximum and minimum components respectively and in consequence the third component, say R, has a magnitude intermediate between P and Q. Before faulting, the plane of maximum shearing stress is normal to the plane containing P and Q. The planes of shear failure (i.e., the planes bounding the slab), while not strictly parallel to the plane of maximum shearing stress, will nevertheless be normal to the plane containing P and Q. R, being also normal to the plane containing P and Q, has no component acting normal to the fault plane. Therefore it does not affect the value of σ_x nor modify the orientation of stress within the slab.

A condition is conceivable, however, in which R could be so large that during fault movement the greatest compressive stress on any axis[4] lying in the P-Q plane could be less than R, in which case the planes of maximum shearing stress within the slab will not be parallel to R but at 45 degrees to R and their trace in the P-Q plane will make an angle of $\beta_1 + 45°$ with the main faults. Thus, for example, if the main faults are vertical and strike-slip, the planes of maximum shearing stress within the slab will dip at 45 degrees.

In fact, in the theoretical case of a fault occasioned by pure shear, (P = − Q), no normal stress whatever acts on the planes of maximum shearing stress. The normal stress on the planes of main fault failure will have either a zero or a small negative (i.e., tensile) value. Thus there would be no friction on the fault planes and no stress within the slab except such as might be occasioned by a third component, R.

[4] The major principal stress in the plane P-Q is:

$$\sigma_1 = \sigma_x/_2 + \sqrt{(\sigma_x/_2)^2 + (\sigma_x\,\mu)^2} = \sigma_x/_2\,(1 + \sqrt{1 + 4\,\mu^2})$$

$$\text{i.e. } \tfrac{1}{2}(P\sin^2\Theta + Q\cos^2\Theta)\,(1 + \sqrt{1 + 4\,\mu^2})$$

Under the conditions originally postulated, namely, failure of homogeneous material in a state of stress whose major axis is parallel to P and (tacitly postulated) a slab bounded by fault planes of infinite extent, any stress, σ_y, normal to σ_x in the plane P-Q must be equal to zero, since no stresses other than those described could "get through" the fault planes. Therefore, barring the special case of a large component of stress on the z-axis (i.e., parallel to R)as just discussed, the orientation of planes of maximum shearing stress within the slab are determined solely by σ_x and the coefficient of friction.

PLANES OF SHEAR FAILURE

Up to this point nothing has been said about the surfaces on which shearing actually takes place within the slab. Of course, no failure will take place unless the stresses in the slab exceed the strength of the rock, but there is in theory no limit to the magnitude that such stresses can attain with increasing load P. According to experimental results and to the Mohr theory of shear failure, which has been advanced to explain them, materials fail in shear planes making angles of less than 45° with the axis of maximum[5] normal stress. Calling this angle θ, the planes of failure within the slab will make angles of:

$$45^\circ - \phi + (45^\circ - \theta) \text{ and } 135^\circ - \phi - (45 - \theta)$$

or

$$90^\circ - \phi - \theta \qquad 90 - \phi + \theta$$

with the main fault (fig. 5D).

A further simplification is possible if it be assumed that $\theta = 45 - \frac{\phi}{2}$. This assumption implies that Navier's "angle of internal friction" is roughly equal to the external angle of friction for sliding surfaces of the same material, an assumption which has little if any basis in theoretical physics but finds some support in experiments by Bouton (Withey and

[5] Compression is here assigned a positive value in accordance with the usual practice in geological literature and contrary to the common conventions of physics.

Aston, 1919, p. 16). With this assumption the angles of shear failure will be

$$45 - \phi + \frac{\phi}{2} \text{ and } 135^\circ - \phi - \frac{\phi}{2}$$

or

$$45 - \frac{\phi}{2} \qquad \text{and } 135^\circ - \frac{3\,\phi}{2}$$

If, for example, the angle of external friction and the angle of internal friction each happened to be 30 degrees, the shears of the second order would make angles of 30° and 90° with the main fault.

ANGULAR RELATION TO INITIAL FORCE

This assumption has a still further implication. The main fault will make an angle of $45^\circ - \frac{\phi}{2}$ with the axis of the initial force, P. Adding this to the angles between the fault plane and the planes of shear failure gives angles of

zero and $90^\circ - \phi$

which would be the angles between the shears of the second order and the initial force, P. This implication, since it involves assumptions that may not be based on sound physics can be considered of only qualitative significance.

THE MORE GENERAL CASE

The special case of a slab between two faults has been selected for explanation because it seemed readily understandable from the intuitive standpoint. The same analysis and conclusions, however, apply to stress orientation in the walls of a single fault plane. It should be noted that after initiation of fault failure there will be shear components of stress parallel and normal to the direction of assumed initial force, P. Also there will be normal stress in a direction Q, at right angles to P.

If these components of stress, normal and parallel to P, are not the boundary stresses at the ultimate margins of a given block, the problem is more complex; the trajectories of stress will be curves rather than straight lines and the formulae

just derived will apply only in the neighborhood of the fault plane.

It is understandable that the coefficient of friction and, therefore, the orientation of stress, may vary during fault movement as static friction changes to kinetic and as the fault plane becomes smoother through the planing action of fault-slip. Furthermore, irregularities in the fault "plane" will introduce local stress concentration and corresponding irregularities in the stress pattern. Therefore faults of the second order will not all make the same angle with the main fault. Indeed it is conceivable that faults of the second order, once in motion will, themselves, cause rearrangement of the stress pattern, thus inducing faults of a third order, but this concept cannot be pursued indefinitely because each fault movement diminishes the energy available from the initial force.

INFLUENCE OF ORIENTATION OF MASTER FAULT

It is apparent from inspection that the larger the angle θ between the initial force and the plane of the master fault, the greater will be the normal component of stress that acts across the fault plane and consequently the greater the shearing component due to friction. While these variations will not affect the *angle* between the master fault and plane of maximum shearing stress in the fault walls, they will effect the *magnitude* of shearing stress, which is a simple function of the normal stress.

If, for any reason there are curves or irregularities in the master fault, movement along it will set up a non-uniform distribution of stress in its walls. Without here attempting to investigate the complexities of non-uniform stress, it should be evident that the magnitude of shearing stress, and therefore the tendency to form shears of the second order, will be greatest in those portions of the fault plane where the attitude of the master fault diverges most widely from parallelism with the direction of initial force.

Tension ruptures would also be likely to develop at such points as in the pattern illustrated in figure 4.

TENSION FRACTURES

If tension fractures develop, they should be parallel to the major axis of compressive stress and thus make angles of

90 — ϕ with the fault. If ϕ is less than 45 degrees, as will commonly be the case, the acute angle that the tension fracture makes with the fault should point in the direction in which the block on its own side of the fault moved, and this is the usual attitude of observed tension fractures adjoining faults.

In some cases, tension fractures, instead of being essentially plane surfaces, execute curves as traced away from the fault plane. The reason for such curvature, whether non-uniform stress-distribution or progressive growth of the fracture, which in itself would occasion progressive change in local stress-orientation, is a matter that calls for investigation both in the field and in the laboratory.

LIMITATIONS

This analysis is intended to apply primarily to steeply dipping strike-slip faults. In such faults the forces due to gravity act in a direction nearly parallel to the fault planes (i.e., vertical) and have no appreciable component either normal or parallel to the faults. Nor would stress-distribution, as viewed in a horizontal section, be modified by proximity to a free boundary (the earth's surface).

The same analysis can apply to normal and reverse faulting but with distinct limitations. It must be assumed that (a) the locality under consideration was relatively deep at the time of faulting, i.e., the influence of a free boundary (the earth's surface) was negligible; and (b) the vertical range under consideration is small compared with its original depth below the surface, so that the variation in gravitative load from top to bottom of the section depicted can be neglected. Such conditions might well have existed during the formation of the fault fissures now exposed within the range of ordinary mine workings, especially in deposits formed at depth appropriate to hypothermal and mesothermal conditions.

In contrast, normal and reverse faults, if viewed on such a scale that the free boundary at the surface and the body force due to gravity come into the picture, present a separate problem. Under such conditions the trajectories of stress are curved surfaces. A special case of this problem, viz., the stress condition above a horizontal thrust plane, has been treated by Hubbert (1951) and by Hafner (1951).

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EARLY TERTIARY VULCANISM IN THE GALISTEO-TONQUE AREA, NORTH-CENTRAL NEW MEXICO

CHARLES E. STEARNS

ABSTRACT. The Espinaso volcanics, newly described, comprise detrital beds deposited by mud flows and streams radiating from centers of contemporaneous eruption in the Ortiz Mountains and Cerrillos Hills, with a few interbedded lava flows. The formation overlies the Galisteo formation without stratigraphic break and is of Duchesnean (latest Eocene) age. A probable vent breccia in the Ortiz Mountains lies close to the focus of a radial dike swarm; a second vent northeast of the Cerrillos Hills, not exposed, is inferred near the focus of another radial dike swarm. Related intrusive bodies exposed in the Cerrillos Hills are stocks and subsidiary sills, laccoliths, and dikes. The intrusive rocks, flows, and fragments in the Espinaso volcanics are principally quartz latite, latite, and monzonite.

The name Cieneguilla limburgite is proposed for a series of flows and associated alluvial beds, younger than the Espinaso volcanics, but older than the Miocene Abiquiu (?) formation.

INTRODUCTION

Preliminary Statement

THE rocks herein described record an episode of volcanic activity in north-central New Mexico during early Tertiary time. Surface eruptions are recorded in the Espinaso volcanics, a formation described for the first time, comprising chiefly detrital beds deposited by streams radiating from centers of contemporary eruption. The volcanic beds overlie the Galisteo formation (Stearns, 1943) without stratigraphic break, and are therefore assigned a Duchesnean (latest Eocene) age. Intrusive rocks related to the Espinaso volcanics have long been known. Those exposed in the Cerrillos Hills were re-examined to evaluate better the working hypothesis of consanguineity with the Espinaso volcanics. The hypothesis is believed to be confirmed, and a principal vent is believed to have lain northeast of the Cerrillos Hills in Espinaso time. It is also believed that the data obtained justify revision of previous interpretations of the structure of intrusive bodies presently exposed in the Cerrillos Hills. They have been previously described as laccoliths, but the majority are crosscutting stocks.

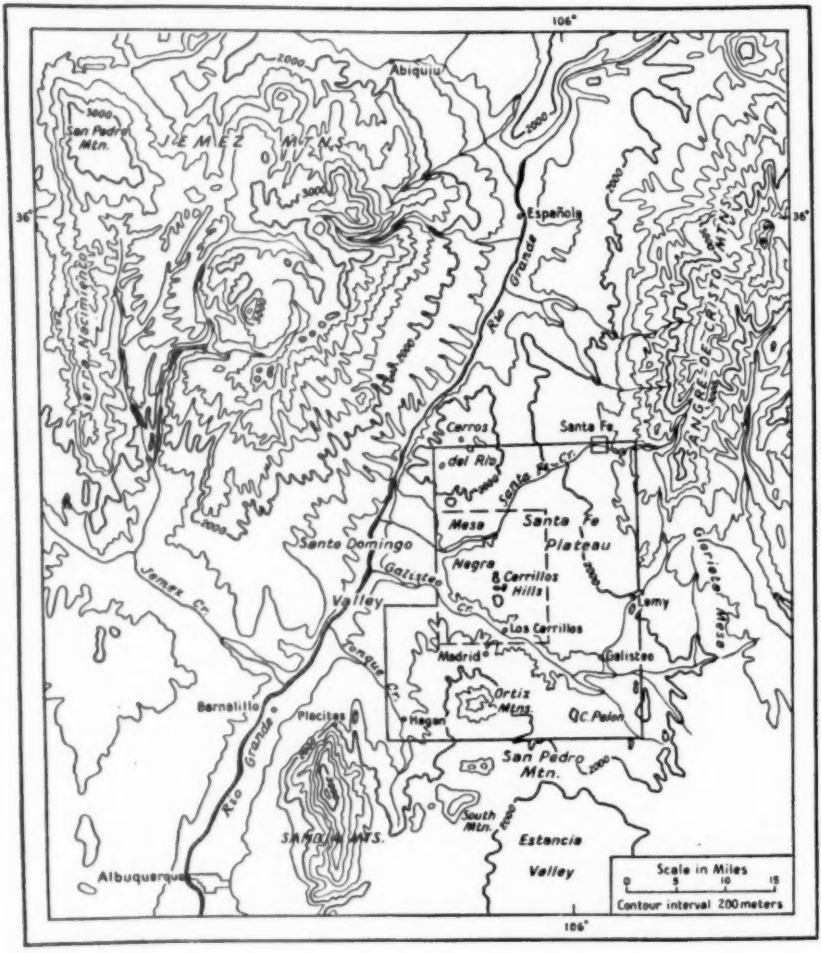


Fig. 1. Topographic map of north-central New Mexico, redrawn from Darton. Area outlined by solid line is shown in figure 2; area outlined by dashed line is shown in figure 3.

A volcanic formation younger than the Espinaso volcanics is described and named the Cieneguilla limburgite. The Cieneguilla limburgite is distinct from the Espinaso volcanics and from late Tertiary lavas of nearby areas in petrography as well as in time.

Regional Setting

Midway between the Sangre de Cristo and Sandia Mountains of north-central New Mexico (fig. 1), a chain of hills extends south from the Cerros del Rio, west of Santa Fe, to South Mountain, northwest of the Estancia Valley. The Cerros del Rio are underlain by lavas of Pliocene and Pleistocene age. The hills farther south, including the Cerrillos Hills, Ortiz Mountains, San Pedro Mountain, and South Mountain, are carved from intrusive rocks. The igneous rocks of South and San Pedro Mountains have invaded Paleozoic sedimentary rocks; those farther north intrude Cretaceous and early Tertiary sedimentary rocks. All the intrusive rocks are of intermediate composition and have generally been interpreted as roughly contemporary intrusions.

Peripheral to the Ortiz Mountains are widespread remnants of the Ortiz pediment, an ancient erosion surface veneered with partially cemented gravels reaching a maximum thickness of at least 150 feet. The pediment is nearly continuous southwest of the Ortiz Mountains, in the saddle between South Mountain and the Sandia Mountains. Southeast of the Ortiz Mountains, the pediment gives way to the higher, gravel-veneered, surface of the Estancia Valley. The Santa Fe Plateau, a broad plain veneered with Pleistocene gravels, slopes southwestward from the Sange de Cristo Mountains to the Cerrillos Hills. Between the Cerrillos Hills and the Cerros del Rio, the plain merges with the Mesa Negra de La Bajada, capped by Pleistocene basalt flows. The west edge of the Mesa Negra, the La Bajada escarpment, overlooks the lowlands of the Santo Domingo Valley, a local subdivision of the Rio Grande Depression, underlain principally by late Tertiary basin deposits (Bryan and Upson, unpublished manuscript). Thus, in much of the area studied, early Tertiary and older rocks are concealed from view.

Between the Santa Fe Plateau and the gravel-veneered Estancia Valley a broad lowland is drained by Galisteo Creek and its tributaries. The lowland is excavated principally in Cretaceous and early Tertiary rocks in a complexly faulted syncline plunging north. The Espinaso volcanics crop out in the trough of the syncline, north of Galisteo Creek. Cerro Pelon, an outlying hill carved from part of a thick sill, rises in the southwest portion of the Galisteo Lowland and isolates a smaller

valley to the southwest, the Canyada Las Jollas. Galisteo Creek flows northwestward from the lowland, through a saddle between the Ortiz Mountains and Cerrillos Hills, to the Santo Domingo Valley, where it joins the Rio Grande.

Between the Ortiz and Sandia Mountains is the Tonque Valley, a lowland excavated in Mesozoic and early Tertiary sedimentary rocks, principally by Tonque Creek and its tributaries. The sedimentary rocks form the west limb of a northward-plunging, faulted syncline. The Espinaso Ridge, type locality of the Espinaso volcanics, is a conspicuous hogback on the northeast side of the valley, forming the topographic boundary between the Tonque and Santo Domingo Valleys.

Previous Work

The attention of early workers was drawn almost entirely to the intrusive rocks and associated ore deposits. Numerous early references are summarized by Johnson (1903), in a detailed account of the geology of the Cerrillos Hills. The importance of his work will be apparent from repeated reference throughout the present paper. He interpreted the intrusive rocks of the Cerrillos Hills as a series of laccoliths, and described the rock types in some detail. He also described the Espinaso volcanics, but his observations of the formation were confined to a limited area.

Ogilvie (1908) published eleven chemical analyses of igneous rocks from the Ortiz Mountains, together with brief petrographic descriptions. She reported that the rocks belonged to a great, differentiated laccolith, but field relations and detailed petrographic data were never published.

The geology of San Pedro and South Mountains was described in a general way by Yung and McCaffery (1903); intrusive rocks in these areas were interpreted as laccoliths. Graton, in a review of the associated ore deposits (Lindgren, Graton, and Gordon, 1910, pp. 163-175) reiterated the general similarity of structure and rock types in the four areas of intrusive activity, and presented additional petrographic data.

Portions of the Espinaso volcanics were studied by Bryan and Upson (unpublished manuscript) in their general survey of the Santo Domingo Valley. These authors have generously made their information available to the present writer, both in manuscript and in conference with the senior author.

Recent studies of some of the intrusive rocks and associated mineral deposits have been carried on by the United States Geological Survey (Smith, et al., 1945; Stoll, 1946).

Methods of Study

The data presented here were assembled in the course of a general areal study of the Galisteo-Tonque area. Field studies were carried on during the summers of 1939, 1940, 1941, and 1946. Field data were plotted on aerial photographs at a scale of 2 inches to the mile, and transferred to planimetric drainage maps, at a scale of 1 inch to the mile. Stratigraphic sections were measured by pace-and-compass traverse. Petrographic studies were made in the laboratories of Harvard University.

Acknowledgments

It is a pleasure to acknowledge deep indebtedness to the late Professor Kirk Bryan of Harvard University, under whose general supervision the study was made. His stimulating direction and unflagging interest, both in the field and in the laboratory, have contributed largely to completion of manuscript. Professor E. S. Larsen, of Harvard University, visited the writer in the field and supervised the petrographic work. Both Professor Larsen and Professor M. P. Billings of Harvard University suggested improvements in the manuscript. Further improvements have been derived from discussions with Dr. Brewster Baldwin, of the New Mexico Bureau of Mines and Mineral Resources, and Mr. Alan Disbrow, of the United States Geological Survey, both of whom have recently mapped portions of the area here described. Numerous local residents, but particularly the Seligman family of Bernalillo and Mrs. J. C. Underwood of Underwood Ranch, contributed materially to the success of the field work.

Aerial photographs and maps were made available through the kindness of Mr. A. C. Blakey, Chief of the Cartographic Division, Rio Grande District, Soil Conservation Service. Field expenses were borne by Dr. A. Warren Stearns. The cost of many of the thin sections was met by a grant from the Milton Fund of Harvard University. Figures 3 and 4 were prepared by Mr. W. N. Palmstrom; figure 1 is the work of Mr. E. A. Schmitz.

The writer was ably assisted in 1939 by A. F. Marston of Tufts College; in 1940, by J. K. Grunig of Harvard University; in 1941, by N. O. Parker of Tufts College; and in 1946, by I. S. Fisher of Harvard University. Mrs. Charles E. Stearns and Miss Beatrice Dole have helped with manuscript.

ESPINASO VOLCANICS

General Description

The Espinaso volcanics comprise at least 1400 feet of volcanic debris. They are described here for the first time, al-

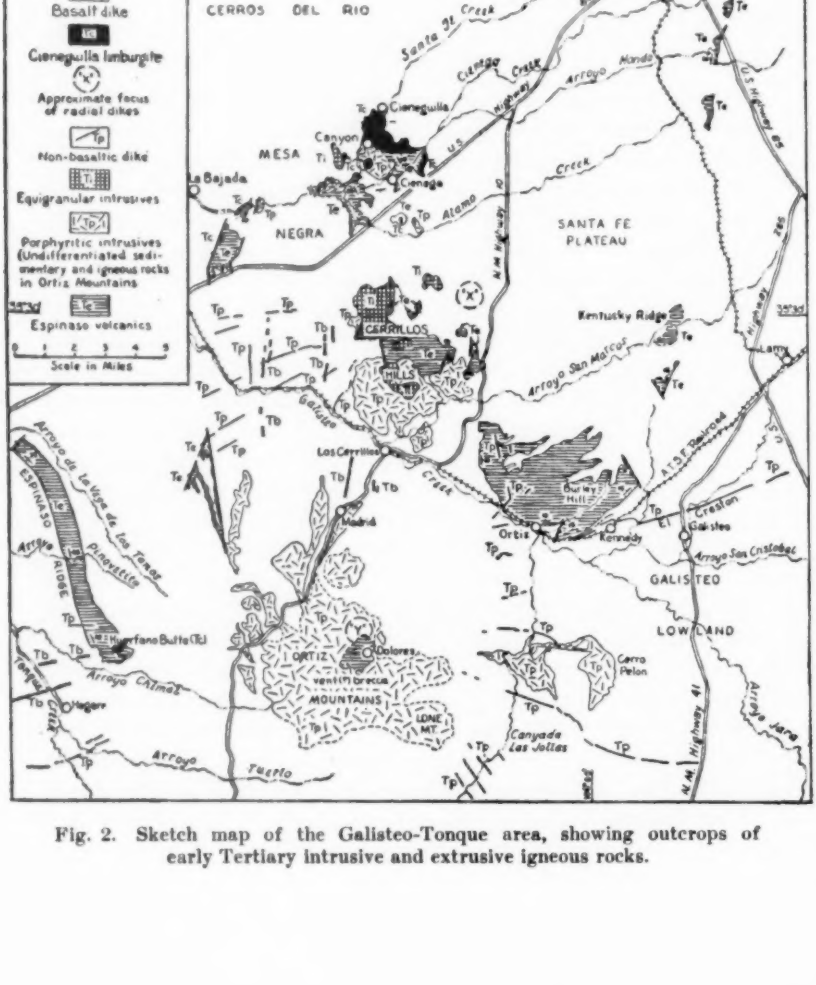


Fig. 2. Sketch map of the Galisteo-Tonque area, showing outcrops of early Tertiary intrusive and extrusive igneous rocks.

though the formation name, assigned in an unpublished study of the Santo Domingo Valley (Bryan and Upson, unpublished manuscript), was published in a description of the underlying Galisteo formation (Stearns, 1943, p. 309). The type locality of the formation is the Espinaso Ridge; the locations of this and other areas of outcrop described below are shown in figure 2.

The Espinaso volcanics conformably overlie the late Eocene Galisteo formation and are overlain unconformably by the Cieneguilla limburgite, by the late Tertiary Abiquiu (?) formation, and by Pleistocene (?) alluvium and basalt.

The bulk of the formation is fragmental (plate 1, figs. 1, 2). Some beds are extremely coarse and contain blocks as much as 10 feet in diameter. Some coarse beds are massive and so poorly sorted that they are presumably mud flows. Rude stratification and sorting, mixture of pebble types in individual beds, and general subangularity of pebbles and boulders imply that most of the material was deposited by streams. Most beds contain pebbles ranging from ½-6 inches in diameter. There are also a few beds of volcanic ash. However, the scarcity of fine-grained beds implies that the depositing streams had high gradients, so that most of the expectable fine components were carried outside the present outcrop area. Lava flows and beds of pumice, scoria, or other identifiable products of explosion are rare. The formation contains the materials appropriate to coalescing alluvial fans on the flanks of an active volcanic center. Blue-gray is the predominant color, but brownish, purplish, and reddish grays are also common. These colors seem to be the original colors of volcanic fragments, and contemporary weathering processes are not recorded. The beds are commonly indurated, and the formation is relatively resistant to erosion.

Rock fragments and pebbles in the Espinaso volcanics are almost entirely latite and quartz latite porphyry. Most of them are characterized by prominent elongate phenocrysts of hornblende or pyroxene. However, tabular phenocrysts of chalky plagioclase are most conspicuous in many of the fragments. Andesite and trachyte occur, but are not common.

Distribution and Lithology

The Espinaso de Clotero Montoya (also known as Pinovetito Ridge) is a hogback 5 miles long (fig. 2), which owes its existence to the relative resistance of the Espinaso volcanics.

The formation is exposed most continuously in the water gap of the Arroyo Pinovetito (plate 1, fig. 1), where the following section was measured:

Abiquiu (?) formation	
Little consolidated gray-white sandstone and orange to buff silt. Scattered lenses carry pebbles 1-6 inches in maximum diameter, of both Espinaso-type porphyry and well-rounded quartzite and chert. Top not exposed.	1200′
Espinaso volcanics	
Discontinuously exposed. Gray, interbedded water-laid breccia and conglomerate. Pebbles and fragments range up to 6 inches in maximum diameter.	150′
Gray, indurated, interbedded water-laid breccia and conglomerate, with minor amounts of water-laid tuff. Pebbles and fragments range up to 2 feet in maximum diameter; some blocks 6 and 8 feet across occur in the upper half of the section. Ridge-forming member.	1050′
Blue-gray, water-laid tuff. A few beds of clay, 1-2 feet thick, near the base; pebbly lenses in the upper half of the section.	200′
Green, tuffaceous clay. Lenses of red clay and limonite-stained sandstone in the lower 25 feet are transitional to the underlying Galisteo formation. Abundant fossil bone occurs in a bed 1-2 feet thick midway of the section (Stearns, 1943, p. 310 and fig. 7).	50′
Total Espinaso volcanics	1450′
Galisteo formation	
Interbedded sandstone, clay, and conglomerate, variegated in color (Stearns, 1943, p. 304-309, fig. 5).	

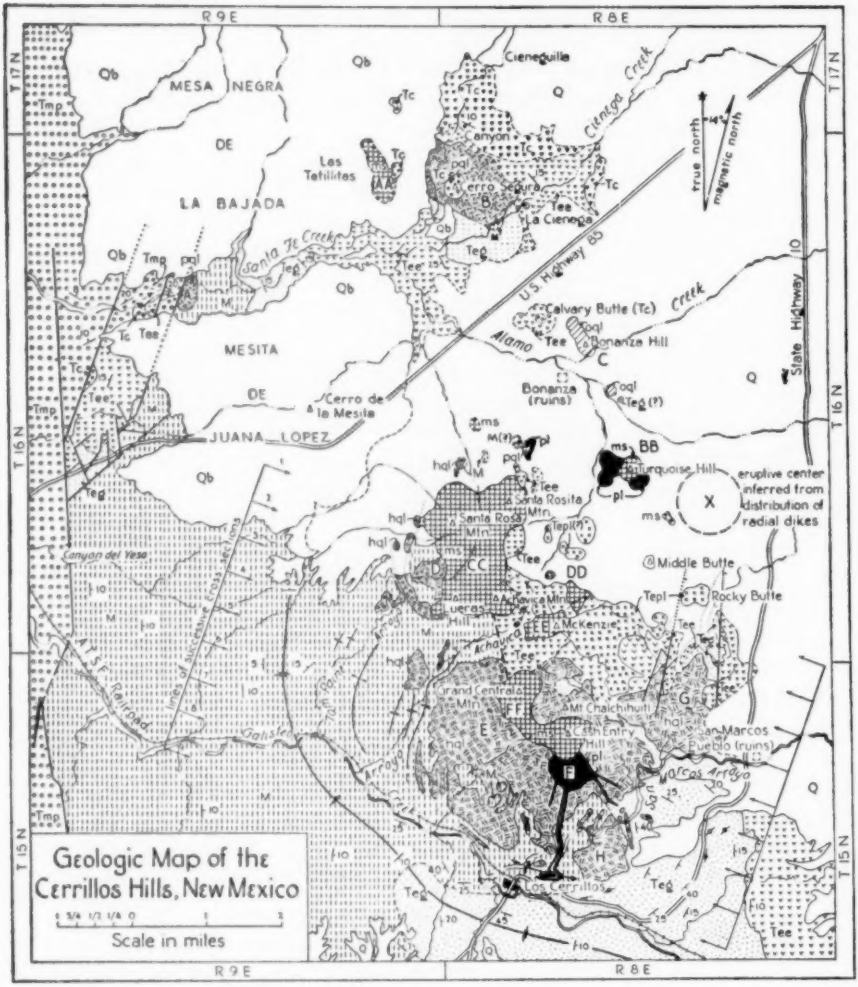
Individual beds are generally massive and discontinuous, and both the lowermost and the uppermost portions of the formation are generally concealed by slope-wash, but there is no conspicuous variation in lithology or coarseness in the 4 miles of outcrop north of the Arroyo Pinovetito. However, two trachyte flows, 10-50 feet thick, occur near the top of the formation at the north end of the Espinaso Ridge. Their lithology is conspicuously different from that of pebbles in beds above and below them. South of the Arroyo Pinovetito the Espinaso Ridge merges with remnants of the widespread Ortiz pediment. However, gravel cover is thin or absent on that part of the pediment underlain by Espinaso volcanics, and the formation can be traced without apparent variation 4 miles southeast to the vicinity of Huerfano Butte. Massive hornblende quartz latite porphyry crops out in a low hogback northwest

of Huerfano Butte and is probably a flow in the Espinaso volcanics. This rock is a type abundantly represented in the fragmental beds.

Four miles northwest of the Ortiz Mountains (fig. 2), indurated water-laid breccia and conglomerate similar to those of the Espinaso Ridge are exposed in a fault slice of complex structure. The beds are stratigraphically higher than nearby exposures of the Galisteo formation. Red and green clays are poorly exposed at the probable contact between the two formations.

The Espinaso volcanics are extensively exposed north of Galisteo Creek, between Ortiz and Kennedy (fig. 2). Northwest of Ortiz, indurated breccia rests abruptly on the underlying Galisteo formation. In the first (unnamed) arroyo south of the Arroyo San Marcos, sandstone lenses typical of the Galisteo formation are intercalated in the lower 100 feet of the volcanics. The overlying beds are massive, but not especially coarse. Stratification is evident in some exposures, but generally not clearly recognizable. In the next arroyo to the southeast, the basal contact is abrupt, but the overlying beds everywhere exhibit at least rude stratification. Some thin beds of massive, unsorted breccia may be pyroclastic, but most of the breccia beds are roughly sorted and probably water-laid. Farther east, near and northeast of Kennedy, the basal contact is less abrupt and is marked by water-laid tuffs. A thin lens of fresh-water limestone was noted in this zone at one locality. Although sections were not measured, at least 1000 feet of the Espinaso volcanics are preserved in the area between Ortiz and Kennedy; they plunge northward under Quaternary gravels. Two latite flows or sills, 50-75 feet thick, form conspicuous hogbacks in the lower part of the formation: Burley Hill, north of Kennedy, and Kentucky Ridge, west of Lamy.

In and east of the Cerrillos Hills (fig. 3) the Espinaso volcanics are involved in deformation and alteration associated with the intrusion of stocks. East of the higher hills, abundant outcrops of water-laid breccia can be identified with certainty in an area mapped by Johnson (1903, geologic map) as intrusive augite andesite. Some water-laid breccia was recognized by Johnson (1903, pp. 75-76) and interpreted as an inclusion, but it is believed that he underestimated its areal extent. In fact, the abundance and continuity of outcrop of the breccia, to-



EXPLANATION

SEDIMENTARY ROCKS

- Q — Quaternary
- Tmp — Late Tertiary
- Teg — Galisteo formation
- M — Mesozoic
- formation contact
- inferred contact (concealed by Quaternary gravel)
- attitude of bedding

EXTRUSIVE IGNEOUS ROCKS

- Qb — Quaternary
- Tc — Cieneguilla limburgite (including small intrusive plugs)
- Tepl — flow in Espinaso volcanics (augite latite)
- Tee — Espinaso volcanics (except massive flows)
- normal fault (showing downthrown side)
- inferred fault (concealed by Quaternary gravel)
- Vertical bedding

INTRUSIVE IGNEOUS ROCKS

- ms — equigranular intrusive rocks (monzonite and syenodiorite)
- pl — augite latite
- pql — pyroxene quartz latite
- oql — orthoclase quartz latite
- hql — hornblende quartz latite
- A — reference symbol of principal known intrusions
- axial trace

Fig. 3.

PLATE 1

Fig. 1. Espinaso volcanics in the Arroyo Pinovetito.

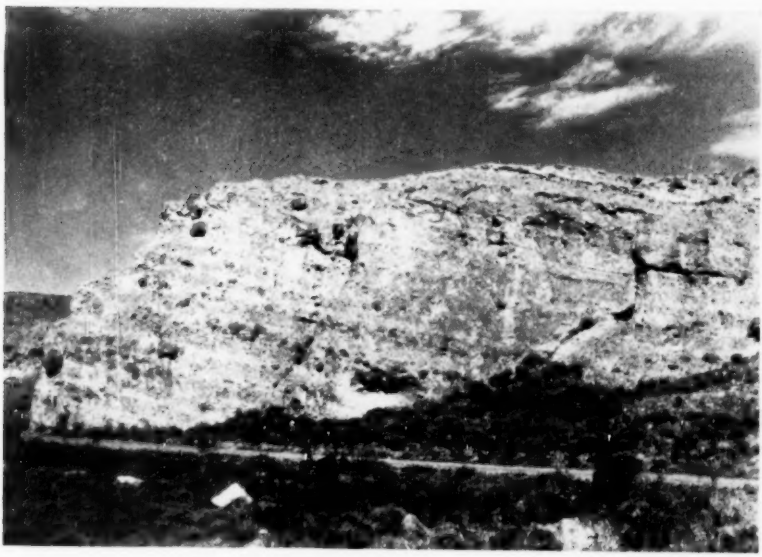


Fig. 2. Espinaso volcanics near La Cienega.

gether with the mappable heterogeneity of the "including" augite latites (= augite-andesite of Johnson), are not consistent with his interpretation. Some small outcrops of massive augite quartz latite, apparently surrounded by breccia and not mapped separately, perhaps represent pipe-like intrusions. However, the principal area of augite latite (fig. 3) is interpreted as a surface flow for the following reasons:

1. Although its outcrop pattern is highly irregular, the southwest boundary roughly parallels the Galisteo-Espinaso contact in so far as the latter is known. The structure of the area underlain by the Espinaso volcanics is not known, but unless the volcanics are very thick they must have low dips. In the latter case, the eroded remnant of a flow interbedded with the breccias would probably have an irregular pattern.

2. Two prominent faults outline a small horst 1 mile southwest of Rocky Butte. The easterly fault continues north of the horst for some distance, with displacement presumably down to the east. The augite latite east of the horst, downfaulted against water-laid breccia north of the horst, is identical with the augite latite farther west described in the previous paragraph. Repetition of the augite latite in the downdropped block implies that the augite latite farther west overlies the water-laid breccia on a contact dipping westward. This relationship is expectable in the case of a flow, but interpretation of the augite latite as an intrusive mass, broken by faulting, demands that its original form be funnel-shaped, flaring widely upward. Such a form is unlikely.

3. Rocky Butte, an isolated hill rising above Quaternary gravels a short distance north of the horst, is an outcrop of the same rock type. Nearly vertical columnar jointing is conspicuous and implies that the rock is part of a flat-lying sheet. Although the butte is isolated from the other outcrops, its geographic position and the strike of beds of the Galisteo formation exposed to the southeast are those which would obtain if Rocky Butte and the outcrops east of the fault described above were remnants of the same flow, dipping gently northwestward.

Massive augite quartz latite, not mapped separately, crops out at several places on the periphery of the augite latite just described. These several outcrops are interpreted as portions of an older flow, but conclusive evidence is lacking.

Northwest of Mt. McKenzie are outcrops of water-laid breccia and probable remnants of the same flow as that exposed east of Mt. McKenzie. A few outcrops of unaltered, water-laid breccia were found on the north flank of Grand Central Mountain. However, in the area between Grand Central Mountain and Mt. McKenzie, extensive alteration by sericitization and kaolinization has obscured the original character of the rocks. Many of the altered rocks are porphyritic and appear to have fragmental texture. In some, the lack of a distinguishable matrix suggests that the "fragments" are outlined by surfaces of shearing and alteration and that the original rocks were massive flow rocks or intrusions. In most, however, an apparent distinction between fragments and matrix suggests that the original rocks were breccias of the flow, explosive, or water-laid types. No rocks of sedimentary origin were identified, although indurated but not highly metamorphosed Cretaceous shale underlies a considerable area northwest of Grand Central Mountain. Mapping of individual rock types in this central area of intense alteration was not possible. The entire area, together with the intrusive rocks of Mt. McKenzie and Grand Central Mountain, was mapped by Johnson (1903, geologic map) as intrusive augite andesite. The altered rocks are certainly porphyritic, and distinct from the granular intrusives of the higher hills; it is believed that most of them belong properly to the Espinaso volcanics. Therefore, this central area is shown (fig. 3) as underlain by Espinaso volcanics, continuous with the adjacent areas to the east, north, and south in which volcanic rocks can be identified with assurance.

In the area northeast of the principal hills, isolated outcrops of water-laid breccia occur in some of the low knolls rising above the level of Quaternary gravels, and others have been encountered by prospect pits near some of the knolls. Other knolls in the same area are formed of massive igneous rocks which may be of either intrusive or extrusive origin.

Several hundred feet of breccia and conglomerate are exposed along the La Bajada escarpment (fig. 3). The conformable contact with the underlying Galisteo formation is abrupt, but lenses containing volcanic pebbles occur in the uppermost 50 feet of the Galisteo formation. Most of the overlying beds are massive, coarse breccias; their general aspect is chaotic. However, the Galisteo formation and immediately overlying beds

are complexly faulted. Although individual faults cannot be traced within the Espinaso volcanics, the apparent lack of continuity of beds probably stems in large part from complex structure. Rude stratification is apparent in most outcrops. Both mud flows and stream deposits probably occur, but their relative importance is uncertain. An estimate of the thickness of the Espinaso volcanics in the outcrop area would have little significance. One mile north, Espinaso volcanics overlain by the Cieneguilla limburgite crop out in the canyon of Santa Fe Creek.

The Espinaso volcanics crop out on the flanks of a small, domal structure near the village of La Cienega (fig. 3; plate 1, fig. 2) in valleys tributary to Santa Fe Creek and in the upper part of the canyon of Santa Fe Creek. Less consolidated, arkosic and volcanic beds are intercalated in a basal zone about 50 feet thick. The overlying beds are similar in a general way to those of the type locality of the formation, but the volcanic fragments are much larger, and massive beds more common. Individual blocks 5 or 6 feet in diameter are not uncommon, and they range to a maximum diameter of 10 feet. Much of the debris was probably deposited in mud flows. A thick lava flow crops out between La Cienega and Cerro Segura. The total thickness of volcanics preserved beneath a cover of Quaternary gravel and basalt appears to be 600-800 feet. Between La Cienega and Canyon, the volcanics were eroded before eruption of the overlying Cieneguilla limburgite, and less than 400 feet of beds remains.

Origin of the Espinaso Volcanics

Deposition of the Espinaso volcanics succeeded that of the underlying Galisteo formation without break. The predominance of fresh, subangular volcanic fragments in mud flows and alluvial beds implies that the formation was largely deposited on great, coalescing, alluvial fans, radiating from centers of contemporary eruption. Small, rotten, rounded volcanic pebbles can generally be found in pebbly lenses of the uppermost few hundred feet of the Galisteo formation. They may have been derived from distant, contemporary, volcanic centers, or from the erosion of older rocks (which must also have been distant). However, the strong and consistent contrast in lithology

between the Galisteo formation and the Espinaso volcanics, with a relatively and in many localities an absolutely abrupt transition, indicates that eruptive centers were formed in or close to the basin of deposition. Volcanic debris was thereby contributed so rapidly as to disrupt the earlier, apparently integrated, drainage of Galisteo time and to exclude perceptible contributions by streams draining the former highland areas. In time, new volcanic highlands, fringed by alluvial fans, were constructed in the former alluvial basin. Present outcrops of the fan deposits are scattered in an area of 350 square miles; the importance of the parent volcanoes cannot be doubted. The question is thus raised: where were the eruptive centers of Espinaso time?

The lithology of the Espinaso volcanics is unlike that of any of the known volcanics of the nearby Valles Mountains (Esper S. Larsen, personal communication in the field). It is also quite unlike the Pliocene and Pleistocene andesites and basalts of the nearby Cerros del Rio. However, fragments in the Espinaso volcanics are petrographically similar to intrusive rocks now exposed in the Ortiz Mountains and Cerrillos Hills.

Messrs. Griswold and Pollock of the Ortiz Mine Grant have kindly shown me a large intrusive mass of volcanic breccia near Dolores (fig. 2; reported by Graton, 1910, p. 168), which probably fills a vent active in Espinaso time. Prominent dikes in the Tonque Valley and Galisteo Lowland are disposed radially to a focus (focus "Y", fig. 2) close to this vent, and presumably fill fractures genetically related to it. The nearest areas of Espinaso outcrop, that north of Ortiz and that in the Espinaso Ridge, are almost equidistant from Dolores and from the Cerrillos Hills. Hence, their geographic positions are not such that eruptions near Dolores would necessarily affect their lithologic character. Nevertheless, it is perhaps significant that a flow, petrographically similar to volcanic fragments in the associated water-laid deposits, crops out near Huerfano Butte, in that portion of the type area closest to Dolores.

The projections of radial dikes exposed southwest and southeast of the Cerrillos Hills (fig. 2) converge in the low-lying area northeast of the hills (focus "X", figs. 2, 3), now largely concealed by Quaternary alluvium. Several low knolls, rising above the alluvium, are formed of massive igneous rocks similar to those exposed in the Cerrillos Hills proper. The outlying

knolls indicate that present exposures of intrusive rock in the Cerrillos Hills reveal only a portion of a large complex of intrusions. Those areas within the Cerrillos Hills which are topographically low are areas of widespread alteration. It may be inferred that alteration is more widespread northeast of the hills, where the bulk of the area is low. It is further inferred that focus "X" is related to an important Espinaso vent, now concealed by alluvium.

In spite of difficulties of interpretation already recounted, flows have been identified between focus "X" and the Cerrillos Hills and there comprise about half of the outcrop area of the Espinaso volcanics. Flows are rare and relatively thin at distances greater than 5 miles from the Cerrillos Hills. Elsewhere, the coarsest detrital beds are exposed at La Cienega. The presence of considerable fine-grained material at the base of the formation in the Espinaso Ridge, and in the area northeast of Kennedy, stands in sharp contrast with the more abrupt contacts in the La Bajada escarpment and northwest of Ortiz. The bulk of the formation appears to be finer grained, too, in the Espinaso Ridge and northeast of Kennedy. The distribution of flows, of grain size, and of contact relations with the Galisteo formation are all consistent with a postulate of contemporaneous eruptions from a vent near focus "X."

The intrusive bodies now exposed in the Cerrillos Hills are younger than those portions of the Espinaso volcanics with which they are in contact. However, the fact that the intrusions do invade the base of the Espinaso volcanics shows that they rose close to the land surface of Espinaso time and makes it probable that some were continuous with surface vents. Such intrusive relationships would necessarily obtain in any vent which was active continuously throughout Espinaso time.

It is concluded that principal eruptive centers of Espinaso time lay near Dolores (vent breccia, fig. 2), and northeast of the present Cerrillos Hills (area "X", figs. 2, 3). Other secondary vents may well have existed. Exposed remnants of the Espinaso volcanics are principally of detrital beds deposited in fans peripheral to the centers of eruption, and are coarse grained at distances of 12 miles from the inferred vents. The original area buried by coalescing fans, exclusive of the fine-grained components which must have been spread over an even greater area, well exceeded the 350 square miles in which

outcrops are known. The parent volcanoes must have ranked among the great volcanic peaks of Tertiary time.

Age and Correlation

The Espinaso volcanics, which overlie beds of the Galisteo formation containing Duchesnean fossils, are of latest Eocene age (Stearns, 1943, p. 311). One diagnostic fossil locality lies in the zone of contact. No direct correlation with other formations in New Mexico can be made now, although it is presumed that further data will establish general contemporaneity with some portions of the Potosí volcanic series of northern New Mexico (Butler, 1946) and of the Datil formation of central New Mexico (Wilpolt, et al., 1946).

Red Beds of the Arroyo Hondo

Four miles south of Santa Fe (fig. 2) the Arroyo Hondo flows in a deep trench cut through thick Quaternary gravels into older rocks for 2 miles west from the foothills of the Sangre de Cristo Mountains. Resting directly on Precambrian granite gneiss are nearly 500 feet of conspicuously red, arkosic and volcanic conglomerate, overlain by two thick flows and by beds of typical Abiquiu (?) and Santa Fe lithology. The following section of the beds was measured by pace-and-compass traverse:

Santa Fe formation	
Pink and buff fan deposits, ranging from sandy silt to sandy gravel. Pebbles predominantly of metamorphic (Precambrian) rocks. Exposed section does not reach the top of the formation.	200′ plus
Abiquiu (?) formation	
Gray-white to light buff, tuffaceous sand and silt. Scattered lenses carry pebbles up to 1 inch in diameter, of both volcanic (early Tertiary) and metamorphic (Precambrian) rock types.	500′
Espinaso volcanics (?)	
Light gray, porphyritic andesite flow, with closely spaced horizontal joints. Upper 25 to 30 feet soft and decomposed.	80′
Discontinuous layer of cinders and buff silt, locally extending downward into underlying flow.	3′
Dark, non-porphyritic andesite flow, with widely spaced horizontal joints locally curving to vertical. Base of flow irregular, incorporating chunks of underlying material.	25′

Espinaso volcanics (?) (cont.)	
Buff to salmon-pink silty sand and tuffaceous clay. Lenses of fine gravel carry pebbles of latite porphyry, stained red.	125′
Deep red conglomerate, with pebbles of latite porphyry up to 6 inches in diameter. Red color is caused principally by staining of pebbles and smaller fragments.	125′
Clay, with local, poorly cemented, gravel lenses.	25′
Deep red conglomerate. Pebbles chiefly of volcanic material, but clusters of Precambrian pebbles occur locally.	50′
Buff to pink, soft, clayey sandstone.	50′
Silty sandstone, in part well bedded, with lenses of conglomerate. Lowermost lenses carry pebbles of chert, limestone, and Precambrian metamorphic rocks. Higher lenses carry volcanic pebbles in addition to other types.	30′
Brick-red, silty sandstone, in part well bedded.	20′
Brick-red conglomerate. Pebbles are 1 to 2½ inches in diameter, chiefly of metamorphic rocks.	8′-15′
Irregular lens of red, silty sandstone.	10′
Irregular breccia, containing angular fragments of the underlying granite gneiss, stained red	0′-35′
Total Espinaso volcanics (?)	575′
Precambrian	
Fine-grained granite gneiss, uniformly stained deep red.	

Similar rocks are found in discontinuous exposures for a distance of 3 miles south from the Arroyo Hondo and for a distance of 4 miles north to the city limits of Santa Fe. The outcrops indicate a lateral variation in lithology. Massive andesite is most abundantly exposed, presumably because of its resistant character. Red sediments also occur, and between the Arroyo Hondo and Santa Fe are several exposures of gray water-laid tuff and gravels. Occasional float of porphyry on the slopes of the Precambrian foothills indicates that the volcanic material once extended east of its present outcrop.

North of Santa Fe, Cabot mapped several areas of pre-Santa Fe volcanic conglomerate and tuff as part of the Picuris tuff (Cabot, 1938, fig. 2). These localities have not been visited by the writer. However, the beds exposed in Little Tesuque Creek 4 miles north of Santa Fe are characterized by deep red color and very probably correspond to those of the Arroyo Hondo (Smith, 1938, p. 943). Those exposed farther north are tuffaceous, but they lack the distinctive red coloration of those to the south. They thus more closely resemble the late Tertiary

rocks of the area, and were included by Denny (1940, p. 683) in the Santa Fe formation.

The red beds of the Arroyo Hondo are an alluvial deposit, to which contemporary volcanism contributed andesite flows and tuffaceous materials. They rest upon an erosion surface with a local relief of at least 35 feet. Coarse, angular breccia in the base of the deposit suggests that relief may have been greater in nearby areas. The arkosic material was undoubtedly derived close to its present outcrop in the Sangre de Cristo Mountains. However, because no Tertiary plugs are known in nearby portions of the Sangre de Cristo Mountains, it is presumed that the volcanic material was contributed by centers of eruption to the west. The red beds of the Arroyo Hondo are strikingly different in color from the generally drab Espinaso volcanics in other localities. The admixture of arkosic and tuffaceous material is also atypical. However, the volcanic pebbles are indistinguishable from pebbles in the Espinaso volcanics elsewhere. It is therefore believed that the Arroyo Hondo beds belong to the formation.

It has been postulated that the Galisteo formation was deposited by streams in large part draining a highland area on the site of the present Sangre de Cristo Mountains (Stearns, 1943, pp. 314-315). The lithology of the Galisteo formation suggests that the source areas were subject to intense chemical weathering, by which most of the limestone was taken into solution and abundant red iron oxides were produced. If fans radiating from a volcanic center impinged upon the lower slopes of a highland previously contributing to the Galisteo formation, sediments like those of the Arroyo Hondo might be deposited. The rate of accumulation on gradients directly opposed to earlier gradients might be appreciably slower than that in other portions of the radial fans. This would permit an admixture of arkosic material in the lower beds by previously existing streams. It would also allow a more complete weathering of the volcanic material, so that it would partake of the color which earlier characterized sediments carried out of the highland area.

INTRUSIVE ROCKS

General Statement

Intrusive igneous rocks crop out extensively in the north-south trending line of hills including South Mountain, San

Pedro Mountain, the Ortiz Mountains, and the Cerrillos Hills (fig. 1). Reconnaissance studies have shown the general similarity of the rocks in the several areas (e. g., Lindgren, Graton, and Gordon, 1910, pp. 163-175). As recognized by Johnson (1903, p. 76), the rocks are also comparable to those of the Espinaso volcanics. In the Cerrillos Hills and at La Cienega (fig. 3) intrusive rocks have invaded and deformed both the Galisteo formation and the Espinaso volcanics. Petrographic similarity implies that their emplacement closely followed the latter formation in time. Pebbles of intrusive and contact metamorphic rocks occur in the Santa Fe formation, showing that the intrusions were exposed to erosion in late Tertiary time.

The intrusive rocks in the Cerrillos Hills and near La Cienega were studied as representative of the entire group. Principal intrusions in the San Pedro and South Mountains have been reported as great laccoliths (Ogilvie, 1908; Yung and McCaffery, 1903), but the complexity of structure found in the Cerrillos Hills is characteristic of the group (Read, et al., 1944, section A-A′; Smith, et al., 1945; Griswold, 1950).

Outside the principal areas of intrusive rock both sills and dikes occur. The sills are quartz latite porphyries identical to some of the rocks of the Cerrillos Hills and are undoubtedly related to them in time and origin.

The dikes for the most part fill fractures radial either to the Ortiz Mountains or to the Cerrillos Hills; several of them form ridges which are conspicuous landmarks. The rocks of the radial dikes include quartz latite porphyries and syenodiorites comparable to known intrusives in the Cerrillos Hills, andesites and andesite porphyries not otherwise recognized as intrusive rocks but comparable to a flow in the Arroyo Hondo which is believed to belong to the Espinaso volcanics, and basalt.

Radial dikes undoubtedly fill fractures genetically related to vents active in Espinaso time, hence formed early in the episode of igneous activity. However, in the Tonque Valley, radial dikes are demonstrably younger than faults which cut sills. Thus, the sills appear to be relatively early, and the dikes relatively late, members of the same petrogenetic series as that of the Cerrillos Hills and Ortiz Mountains. Intrusion of the dikes may postdate formation of the radial fractures by an appreciable interval. However, age relationships can be established only in this general way. None of the radial dikes are known to cut the Abiquiu (?) or Santa Fe formations.

A swarm of basalt dikes trending north-south crops out west of the Cerrillos Hills. Two of the dikes cut radial dikes of quartz latite porphyry; they are presumably related to the basaltic lavas of the Mesa Negra. Limburgite dikes comparable to flow rocks of the Cieneguilla basalt were noted near La Cienega and in three isolated localities in the Cerrillos Hills.

Cerrillos Hills

Strong local deformation is associated with igneous intrusions in the Cerrillos Hills. The complex structure of the sedimentary rocks adjacent to the hills, including the Galisteo formation, stands in striking contrast to gentle easterly dips both east and west of the hills. The obvious spatial association of strong deformation with intrusion and the local concordance of structure led Johnson to describe the intrusive bodies as laccoliths (1903, pp. 463-471). "Regarding the exact number and relations of the several laccoliths," he expressed considerable doubt (idem, p. 467). However, he suggested that the intrusive rocks of the hills probably belonged to laccolithic intrusions of two ages, an earlier series comprised of hornblende andesites and a later series comprised of augite andesite, gabbro-porphyry, and augite-monzonite porphyries. The coarser-grained gabbro and monzonite were presumably interpreted as central coarse phases of laccolithic bodies, and were not mapped separately.

Although considerable uncertainty still exists in some areas,[1] it is believed possible to obtain a more adequate solution of the underlying structure of the Cerrillos Hills. Johnson believed the intrusions to be laccolithic, but he was unable to establish the presence of a floor, and his cross sections do not indicate laccolithic form. The present writer's interpretation of the structure is shown in a series of sections at intervals of about ½ mile (fig. 4). The local deformation appears to be associated with intrusions of hornblende quartz latite porphyry, each earlier than all other intrusions which can be related to it in time. One (intrusion "D", fig. 3) is partially exposed in Tom Paine Arroyo, northwest of Lueras Hill (sec. 1-3, fig. 4). If originally symmetrical, the body was probably elliptical in plan, with axes of ¾ mile and at least 1¼ miles. It is now

[1] The United States Geological Survey has recently mapped much of the area at a scale of 1000 feet to the inch. However, this map is not yet available to general use.

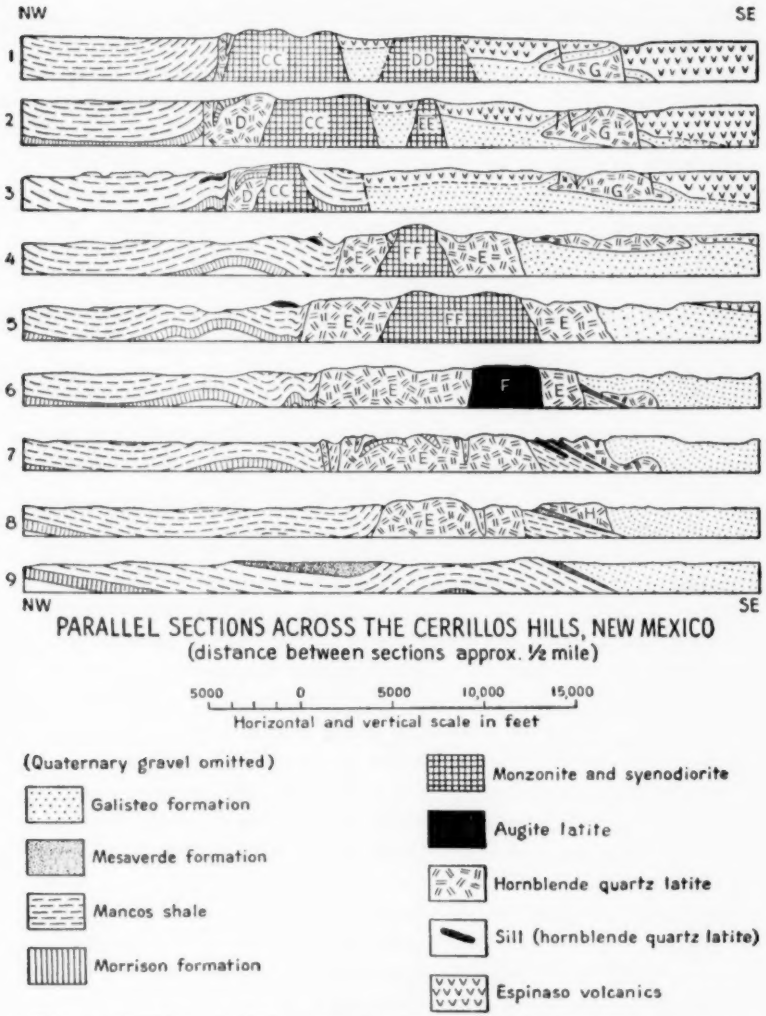


Fig. 4. Structure sections across the Cerrillos Hills. Locations of sections are shown in figure 3.

cut off on the northeast by a later intrusion of monzonite (intrusion "CC", figs. 3, 4). Beds of the Morrison (?) formation and Mancos shale dip steeply to vertically on the southern and western margins, with essential concordance. Peripheral intrusive sheets occur in vertical beds. One of them is a thin

sill continuous in gently dipping beds away from the intrusive, and is probably older than the principal intrusion. However, as shown in cross section, the other nearly vertical sheet is believed to be a dike-like apophysis of the main intrusion. Although it has the form of a sill at the present level of exposure, maintenance of that form at depth would require that it follow bedding planes away from the main intrusion: it would further imply that it had been fed from above, and injected downward into beds flanking the main intrusion. The alternative hypothesis, that it was injected upward as a dike-like apophysis which took the form of a sill where bedding planes approximated the vertical, is more credible mechanically. Arching beds of the Morrison (?) formation appear to represent portions of an original roof, and inclusions of sandstone in the younger monzonite imply that the roof was once more extensive. The dike-like apophysis appears to have conformed to bedding in the arch (see sec. 3, fig. 4). It also appears to be essentially continuous in the area now exposed to view; in part of this distance the dike is multiple, subdivided by thin shale partings, but they do not interrupt its general continuity. If this continuity were maintained around the entire periphery of the original "main intrusion," the arched roof would obviously be detached from the rocks outside the peripheral sheet. In fact, although more than half of the original intrusion is now lacking, the relationships of both sections 2 and 3 suggest that the "main intrusion" grew upward by a combination of (1) arching of the overlying beds, (2) a form of stoping, in which dike-like apophyses, injected into steeply dipping beds on the flanks of the arch, followed bedding planes across the arch and helped to detach large blocks of the roof. This form of stoping, guided by fractures arching steeply over the magma reservoir, is rather similar to that postulated in underground cauldron subsidence (Billings, 1946, pp. 284-285, fig. 234). No evidence of a floor has been forthcoming, and in its absence the intrusion is best interpreted as a small stock, forcefully intruded and very probably partially roofed within the Morrison (?) formation.

A larger body of hornblende quartz latite porphyry occupies a roughly circular area about 3 miles in diameter, immediately north of Galisteo Creek (intrusion "E", figs. 3, 4). The immediately adjacent sedimentary rocks generally dip away from

the mass at high angles, in striking contrast to the prevailing low dips at a distance from the intrusion. It is obvious that strong deformation accompanied intrusion of the hornblende quartz latite porphyry, but it is in fact a discordant mass. To the west and southwest, beds of the Mancos shale dip steeply, even vertically, in apparent concordance to the intrusive contact. However, as indicated in sections 4-7 (fig. 4), the apparent concordance in horizontal section probably does not exist in vertical section. The shales are sharply folded near the contact, and folds of lesser intensity occur away from the contact; axial traces are parallel to the contact. These relations imply that the folding was produced by active lateral expansion of the intrusive body. To the east and southeast, the igneous body is in intrusive contact with all formations from the Mancos shale to, and including, the Espinaso volcanics, thus cutting across a stratigraphic section of about 4000 feet in a horizontal distance only twice as great. Several small dikes, sills, and laccoliths of the same rock type are peripheral to the main body.

In the southwest portion of intrusion "E" are several xenoliths of Morrison (?) sandstone and Mancos shale, the largest more than ½ mile long (fig. 3; sec. 7, 8, fig. 4). Bedding planes of the xenoliths generally strike parallel to the margins of the intrusion. The distribution of xenoliths suggests that at least part of intrusion "E," like intrusion "D," may have at one time been roofed within the Morrison (?) formation, and that a portion of the roof was broken up by the process visualized earlier. In this disintegration of the roof, at least one formerly peripheral sheet on the west margin was fused with the main stock. Perhaps the present discordant relations on the east margins of the body were developed at this time, and the body concomitantly grew eastward as well as upward. It is also possible that the northeastern portion of the now continuous mass was originally a separate, crosscutting intrusion, and that in the later stages of intrusion a septum between it and an actively growing roofed intrusion to the west was broken.

It should be noted that north of Mt. Chalchihuitl (fig. 3) intrusion "E" invades the Espinaso volcanics; along the Arroyo San Marcos, it cuts across most of the Galisteo formation. There is no formation stratigraphically higher than the Espi-

naso volcanics and older than intrusion "E"; these relationships strongly imply that part of the magma reached the surface before solidifying. The extrusive rocks formed, of course, cannot be represented among the basal Espinaso volcanics north of Mt. Chalchihuitl. Surface eruptions from the vent, if they occurred, were at least as late as late Espinaso time.

There seems to be no reason for calling the highly irregular body a laccolith. It was emplaced in part by forceful injection, and present relationships suggest that at one stage at least part of the body was roofed by arching beds of the Morrison (?) formation. However, there is no evidence of a floor. The lateral expansion indicated by folding west of intrusion "E" would require intense stretching and probably fragmentation of the roof; xenoliths of the Morrison (?) formation attest to the fragmentation. Stoping played a large part in the emplacement.

In summary, intrusions "D" and "E" appear to resemble the central stocks of the Henry Mountains, as recently described by Hunt (1942, 1946). With laccoliths they share the existence, at least during part of their development, of a domed roof. However, they are not floored; in vertical section they are crosscutting.

A small body of hornblende quartz latite porphyry south of the Arroyo San Marcos (intrusion "H", figs. 3, 4) is probably a true laccolith. Along its western margin, sandstone and shale of the Mesaverde formation crop out in bluffs below and apparently dipping underneath the intrusive rock. On the south and east, beds of the Galisteo formation dip steeply eastward (locally, they are vertical or overturned) in apparent conformity to the intrusive rock. Similar sharp deformation in the Galisteo formation continues 2 miles east of the present exposures of igneous rock; the axial trace of an anticline defined by the deformation is concealed by Quaternary gravels. As shown in sections 6 and 7 (fig. 4), it is presumed that the anticline covers an eastward extension of the exposed laccolith.

A larger body of hornblende quartz latite porphyry north of the Arroyo San Marcos (intrusion "G", figs. 3, 4) is probably also a laccolith. Along its southern margin, beds of the Galisteo formation dip northward, apparently under intrusive rock. The northern margin is highly irregular and is broken by faults which appear to die out southward in intrusion "G."

However, the intrusion is everywhere in contact with beds of the Galisteo formation and of the Espinaso volcanics. The beds are conformable to the intrusion in a general way, and the stratigraphic range of crosscutting is probably less than 200 feet. Interpretation of the intrusion as a laccolith, the roof of which is modified by stoping and broken by faulting, is in accord with field relations as known.

A roughly circular plug of augite latite porphyry (intrusion "F", figs. 3, 4) cuts hornblende quartz latite porphyry south of Cash Entry Hill. From it radiates a series of dikes (five of the larger dikes are shown in figure 3). Two of the dikes, only a few yards apart, extend 1 mile south into steeply dipping Mancos shale. After cutting across the beds for some distance, the dikes break into and become conformable to the bedding. The southern ends, as sills, follow the bedding faithfully around the nose of a steeply plunging anticline in the Mancos shale. The conclusion seems justified that the dikes were emplaced after deformation of the Mancos shale, taking the form of sills where the steep inclination of the beds approximated the attitude of the dikes. If this is true, the intense local deformation of the sedimentary rocks adjacent to the Cerrillos Hills was probably accomplished entirely during intrusion of the older bodies of hornblende quartz latite porphyry.

Granular intrusives—monzonite, quartz-bearing monzonite, and syenodiorite—form the high hills of the Cerrillos group (intrusions "CC", "DD", "EE", "FF"; figs. 3, 4). There is a high degree of correspondence between lithology and topography. The hills are uniformly composed of granular intrusives. The bordering, gravel-covered surfaces, where exposures are available, are underlain by other rock types. Contacts, however, are concealed by slope rubble. Outcrop patterns indicate that the margins of the granular intrusives are rather regular in trace. A stope breccia of indurated Mancos shale about 3 feet wide is exposed at one locality on the south side of Achavica Mountain.

In areal pattern, the granular intrusives cut across the structures of the older rocks. This is best shown in the vicinity of Tom Paine Arroyo, where monzonite of intrusion "CC" cuts cleanly across intrusion "D" and part of its domed roof (fig. 3; sec. 1-3, fig. 4). The granular intrusives therefore occupy space once occupied by other rocks. This space was won by stoping rather than by pushing the earlier rocks aside. The

rocks now adjacent to the granular intrusives do not appear to have been deformed by their intrusion.

Igneous rocks crop out in several low hillocks rising above the gravel-veneered surface northeast of the Cerrillos Hills proper. Their relationships to rocks other than the younger gravels are indeterminate. However, the existence of a major eruptive center (area "X", figs. 2, 3) has been inferred from the distribution of radial dikes. The importance of this gravel-veneered area cannot be overemphasized, but the number and form of intrusions now concealed from view is unknown.

In summary, the intrusions now exposed in the Cerrillos Hills are divisible into two groups, probably separated by a significant interval of time. The two groups are similar in their generally intermediate composition, but differ consistently in texture and habit of intrusion. The first group comprises (a) stocks of hornblende quartz latite porphyry (intrusions "D", "E"; figs. 3, 4); (b) peripheral laccoliths, sills, and dikes of the same rock type (including intrusions "G", "H"; figs. 3, 4); and (c) a small stock of augite latite porphyry, with associated radial dikes (intrusion "F"). All are fine-grained porphyries, and all bear evidence of forceful intrusion in part. These rocks are petrographically identical to extrusive rocks of the Espinaso volcanics. Although the exposed intrusions are younger than adjacent volcanic rocks, essential continuity with late Espinaso vents in space and in time may be inferred. The principal eruptive center of Espinaso time is believed to have lain northeast of the Cerrillos Hills in area "X" (figs. 3, 4). This area is placed asymmetrically with respect to the intrusive rocks now exposed, which probably include subsidiary vents.

The second group comprises irregular, crosscutting stocks of equigranular rocks (intrusions "CC", "DD", "EE", "FF"). They must have cooled at shallow depths, but there is no compelling evidence that they were ever continuous with surface vents.

Although subsidiary sills and laccoliths occur, including two masses of moderate size (intrusions "G", "H"; figs. 3, 4), the principal intrusive bodies are crosscutting. Previous interpretations of general laccolithic form are not supported by detailed mapping. Similar relations apparently obtain in the related areas of igneous activity south of the Cerrillos Hills.

La Cienega

An irregular intrusion (intrusion "B", fig. 3) of augite quartz latite crops out north of La Cienega. To the northwest, the quartz latite is overlain unconformably by Pleistocene basalt; to the northeast, unconformably by the Cieneguilla limburgite. To the south, the Galisteo formation and Espinaso volcanics crop out in a domal structure. Both formations are sheared in a narrow zone adjacent to contacts with intrusion "B," and in the arroyo banks near the bridge at La Cienega are a few outcrops of Mancos shale which must have been dragged up along the intrusive contact. Intrusion of the quartz latite was obviously forceful. The intrusive body now crops out on the flank of the dome, and it is more discordant than concordant. However, the domal structure finds its most ready explanation as deformation associated with igneous intrusion at depth. The augite quartz latite now exposed may be an offshoot of that intrusion, formed after the domal structure was outlined, or a younger, independent body.

PETROGRAPHY OF THE EARLY TERTIARY IGNEOUS ROCKS

Petrographic studies of the early Tertiary igneous rocks were initiated in 1941 to test the inferred genetic relationship between Espinaso volcanics and intrusive rocks of the Cerrillos Hills. The work was interrupted during the war, and field studies of the Cerrillos Hills were conducted by the United States Geological Survey in 1945 (Stoll, 1946). Eventual publication of a detailed report is planned (W. H. Bradley, personal communication to Professor Kirk Bryan, 1946) and further petrographic study by the writer has seemed inadvisable. The results so far obtained are recorded in summary form (tables 1, 2), and some general inferences may be drawn from the data at hand, although they are incomplete.

The intrusive rocks of the Cerrillos Hills are divisible into two main groups on the basis of grain size. The first group is a series of fine-grained porphyries, the second a series of medium-grained, equigranular rocks. What evidence there is suggests that the division may separate rocks of slightly different ages and of different structural characteristics. The mineralogy of the two series (tables 1, 2) is rather uniform and, although some range of composition occurs within each

TABLE 1

Estimated Modes of Fine-grained Porphyries

| | | |

TABLE 2

Estimated Modes of Equigranular Intrusives

	Monzonite Sta Rosa Mtn.	Monzonite Achavica Mtn.	Monzonite Grand Central	Syenodiorite * Mt. McKenzie	Monzonite Tetillitas
plagioclase	40	50	40	60	45
orthoclase	30	40	40	6	45
quartz		2	2		
hornblende			5		
pyroxene	20	5	5	22	5
biotite	3	1	3	4	
opaque oxides	6	3	4	7	5
olivine	1				
apatite	x	x	x	x	1
sphene		x	1		
epidote			x		
zircon			x		

x: less than 1%

* Mode by Rosiwal analysis

rocks in which quartz is specifically identifiable in the groundmass have been called quartz latites, the remainder latites.

Lithologically, the extrusive Espinaso volcanics and the intrusive porphyries of the Ortiz-Cerrillos chain are similar. Variations in lithology are more apparent within the two groups than between them. Neither in hand specimen nor in thin section can an isolated specimen be classed as intrusive or extrusive; field relations are the only sure means of distinction. Many isolated outcrops cannot be definitely identified as intrusive or extrusive on the basis of field relations. This is, of course, true of the low hills rising above Pleistocene gravel north and east of the Cerrillos Hills proper. The consanguineity inferred from field data is confirmed by petrographic examination.

The groundmass textures of the fine-grained porphyries, presumably the products of relatively rapid cooling, are what one might expect in extrusive rocks. Some of the Espinaso rocks are flows, but the great bulk are fragmental. The environments under which the latter rocks actually crystallized are therefore not precisely known. Many of them may have crystallized in small conduits, and later have been ejected by explosion, rather than after extrusion onto the surface in liquid form. In the area of the Cerrillos Hills, field relations show clearly that some masses are intrusive bodies. The largest known mass (intrusion "E", fig. 3) occupies an area of outcrop roughly 3 miles in diameter. Neither in this nor in the smaller bodies is there significant variation in texture, even at their margins.

The younger granular intrusives (intrusions "CC", "DD", "EE", "FF"; fig. 3) are medium grained and almost entirely non-porphyritic. They presumably crystallized more slowly, under conditions more nearly approaching equilibrium. The equigranular rocks occur in bodies no larger than those of fine-grained porphyry. Some are smaller. There is no striking chemical or mineralogical dissimilarity between the two groups, as far as is known. Some significant and constant difference in environment during the periods of crystallization is therefore implied. The difference may have been one of thermal conditions in the host rocks at the time of intrusion, or in the effectiveness of those rocks in confining fugitive constituents of the magmas. One may infer that a significant difference in environment developed in the interval between two somewhat distinct episodes of intrusion.

CIENEGUILLA LIMBURGITE

Distribution and Lithology

The name Cieneguilla limburgite is here proposed for a series of flows and ejectamenta, with associated water-laid beds, exposed in the vicinity of La Cienega. The flows are nearly all limburgites, petrologically distinct from any of the late Tertiary or Pleistocene basalts of the Mesa Negra and the Cerros del Rio. The type locality is taken as the canyon of Santa Fe Creek, between the small settlements of Canyon and Cieneguilla (fig. 3), where the following section was measured:

Unconformity: At Cieneguilla, the Cieneguilla limburgite is overlain with angular unconformity by Pleistocene alluvium of the Santa Fe plateau, Pleistocene basalt of the Mesa Negra, and by younger alluvium in Santa Fe Creek.	
Limburgite flow or flows.	50′
Purple, tuffaceous sand, containing fragments and pebbles of limburgite.	10′
Limburgite flow or flows.	75′
Intermingled buff silty sand, basaltic cinders, and decomposed limburgite.	20′
Buff silty sand, containing fragments of limburgite.	10′
Limburgite flow or flows, largely decomposed.	100′
Limburgite flow, decomposed along joints.	50′
Buff, indurated basaltic ash and cinders. Thickness varies on strike from 0-8 feet, generally about 1 foot. Contains bombs of limburgite, some containing cores of granular latite or syenite porphyry.	1′
Limburgite flow, closely jointed. Joints and vesicles at top of flow impregnated by calcite.	20′
Gray to buff pebbly sand and gravel, containing pebbles of gray latite (?) porphyry and decomposed, amygdaloidal limburgite or basalt. Discontinuous on strike.	5′
Limburgite flow, top of flow jointed, decomposed, and impregnated with calcite.	25′
Coarse, purplish, tuffaceous sand, moderately indurated.	15′
Concealed.	15′
Limburgite flow (crops out on east wall of valley, does not crop out on valley floor).	40′
Discontinuous exposures, chiefly buff or purplish gray pebbly sand and gravel, containing pebbles of gray latite (?) porphyry and decomposed, amygdaloidal basalt.	50′
Limburgite (?) flow (exposed on east wall of valley, does not crop out on valley floor).	10′
Discontinuous exposures, sand and gravel as above.	20′

Basalt flow.	25′
Buff and gray pebbly sand and gravel, with thin lenses of sandy or clayey silt, moderately indurated. Rounded pebbles of gray latite (?) porphyry and decomposed, amygdaloidal basalt average ½-1 inch in maximum diameter; latite pebbles attain a maximum of 6 inches. ..	25′
Reddish buff, decomposed basaltic cinders.	10′
Pebbly sand and gravel as above.	15′
Total Cieneguilla limburgite	590′
Concealed. The base of the section is not exposed, and the nature of the contact with underlying beds therefore not shown. The maximum stratigraphic interval concealed is estimated to be 50 feet.	
Espinaso volcanics. Purple drab breccia, containing fragments of latite porphyry in a tuffaceous matrix.	

The individual flows vary in thickness and apparently in continuity along the strike. In the lower part of the section, where the valley of Santa Fe Creek is broad, attempts to trace flows across the valley were not successful, and it is possible that the relative amount of water-laid sediments in the section is higher in the valley bottom. The limburgite flows are more commonly characterized by platey rather than columnar jointing. The topmost few feet of some of the flows are amygdaloidal, but the bulk of each flow is massive.

Northwest of Santa Fe Creek, Pleistocene basalt of the Mesa Negra overlies the Cieneguilla limburgite with angular unconformity and conceals it from view. Two isolated outcrops of limburgite, rising above the general level of the mesa, indicate that the Cieneguilla limburgite extends at least 1 mile to the northwest beneath the younger lavas.

Southeast of Santa Fe Creek, outcrops of limburgite in a line of low hogbacks carry the outcrop of the formation to the valley of Cienega Creek. Along the Canyon-Cienega road the Cieneguilla limburgite apparently overlies a mass of augite quartz latite intruding the Espinaso volcanics. A contact between the intrusive and the overlying basalts has not been seen. Sediments such as occur at the base of the formation at Canyon do not crop out near the road, and the base of the formation appears to lie at least 100 feet higher stratigraphically than it does at Canyon.

Cerro Segura (fig. 3), a hill rising above and entirely surrounded by the augite quartz latite, is composed of massive

limburgite. Inclusions of granular porphyries, similar to those observed in bombs contained in the Cieneguilla limburgite, are common in some outcrops. The trace of the contact between the limburgite and the augite quartz latite can be mapped across the gulches and spurs flanking Cerro Segura with sufficient accuracy to show that it is a nearly vertical contact. The limburgite of this hill is therefore a nearly circular plug intruding the augite quartz latite. It is, of course, younger than the augite quartz latite, and was undoubtedly the source of some of the Cieneguilla flows. It follows that the Cieneguilla limburgite is younger than the augite quartz latite, and separated by a time interval sufficient for the development of an erosional surface cutting across the older intrusive body. The absence of any thickness of water-laid sediments where the Cieneguilla limburgite overlies the intrusive body implies that this erosional surface possessed considerable local relief.

Four widely scattered outcrops of limburgite are correlated with the Cieneguilla limburgite because of their striking lithologic similarity, distinct from any other rocks known in the Galisteo-Tonque area. In all four localities the stratigraphic or structural relations of the limburgite are such that a correlation with the Cieneguilla limburgite is possible.

1. Limburgite caps the small conical hill known as Cerro de la Cruz or Calvary Butte 1 mile south of La Cienega (fig. 3). The hill, an erosional remnant, is a nearly perfect cone. Its summit is a massive outcrop. A calichified rubble of limburgite blocks mantles its slopes, effectively blanketing the underlying rocks. A small nubbin, projecting to the west from the base of the hill, is composed of Espinaso breccias. The structural relationships of the limburgite are unknown. It may be the surface exposure of a small plug or the last remnant of a once more extensive capping flow.

2. Limburgite flows crop out in the canyon of Santa Fe Creek 2 miles east of La Bajada (fig. 3), underlain by Espinaso volcanics and overlain by the Abiquiu (?) formation.

3. Remnants of a limburgite flow directly overlie Espinaso breccias in the La Bajada escarpment (fig. 3). Inclusions of gray latite (?) porphyry were observed in the limburgite. To the west, the Abiquiu (?) formation is downfaulted against the limburgite and underlying Espinaso volcanics.

4. Huerfano Butte, a small hillock rising above the Ortiz pediment north of Hagan (fig. 2), is capped by limburgite. Most of the surface material is coarse rubble, but it must be underlain by massive limburgite. Espinaso volcanics are exposed on the lower slopes of the hillock and on adjacent portions of the pediment surface. The form of the hill and the trace of the lower limit of limburgite blocks on its slopes suggest that the hill is capped by a limburgite flow dipping northward more gently than the underlying volcanics. However, the flat contact probably does not exist and the outcrop is that of an intrusive plug. In gulches a short distance north of Huerfano Butte the Espinaso volcanics are overlain directly by the Abiquiu (?) formation. The beds of the Abiquiu (?) formation dip to the north more gently than do those of the Espinaso volcanics, but more steeply than the inferred dip of the limburgite on Huerfano Butte. As the limburgite is older than the Abiquiu (?) formation, as proved in the La Bajada escarpment, the lack of limburgite north of Huerfano Butte implies that Huerfano Butte is the surface exposure of an isolated plug.

Age

The Cieneguilla limburgite is younger than the late Eocene Espinaso volcanics, and separated from them by a time interval during which a small body of augite quartz latite was intruded, solidified, and exposed by subsequent erosion. In the type locality, an upper limit to the age of the Cieneguilla limburgite is provided only by gentle deformation and erosion prior to the extrusion of Pleistocene basalt. In the canyon of Santa Fe Creek, however, the Abiquiu (?) formation overlies limburgite flows, showing that the Cieneguilla limburgite is pre-Abiquiu (?) and therefore pre-Miocene.

The Cieneguilla limburgite thus appears to be Oligocene or earliest Miocene. The flows and associated tuffs belong to that interval during which the volcanic landscape of late Espinaso time was effaced and during which the geographic pattern of Abiquiu (?) time was developed. The relative position of the Cieneguilla limburgite in that interval cannot be inferred from present scattered outcrops of the formation. It serves to emphasize the probable complexity of an interval of which scant record is left for present inspection.

Petrography of the Limburgites

Megascopic.—The rocks are black and dense. Phenocrysts of olivine, either amber or reddish, are generally conspicuous by their luster. Cavities are rare. Small, yellowish spots in one or two specimens indicate their presence. In many places the flows are thoroughly jointed and altered.

Microscopic.—Abundant phenocrysts of olivine are large and fresh, although generally slightly stained by iron oxide along fractures. Less commonly, they are altered to iddingsite or serpentine along fractures. Small phenocrysts of augite and biotite, the latter mineral probably late, occur in a few specimens.

The groundmasses are very fine grained. Stubby grains of clinopyroxene generally form more than half of the groundmass. They are set in a weakly birefringent groundmass of low index which is believed to be generally zeolitic. In two specimens, nepheline occurs in anhedral masses of moderate size, poikilitically enclosing the clinopyroxene. Heavy liquid separations fail to separate much of the groundmass; a few grains of plagioclase were found in one separation. Small mariolitic cavities are filled by analcite or zeolites.

The plug of Cerro Segura carries numerous inclusions of a light gray, granular rock. The inclusions are composed chiefly of large, anhedral orthoclase. Tiny grains and, near the borders, slender needles of clinopyroxene and small plates of biotite also occur. Interstitial to the orthoclase is a turbid, pale brownish material with a mean index slightly below that of the orthoclase. Some of the orthoclase appears to have been altered to similar material. The including limburgite contains a few corroded phenocrysts of plagioclase and orthoclase which are believed to be foreign.

The plug (?) of Calvary Butte carries numerous small, greenish inclusions (?). These are composed chiefly of fibrous hydronephelite, with smaller amounts of clinopyroxene, a deep brown, non-pleochroic mineral, and a pale green alteration product. The inclusions may have originally been rocks similar to those included in the Cerro Segura plug, here more thoroughly reworked by the limburgite. The absence of foreign phenocrysts in the including limburgite at Calvary Butte may support the inference of a more thorough reworking by the magma.

TABLE 3

Analysis of Limburgite from Calvary Butte

(F. E. Gonyer, analyst)

	Newly analyzed limburgite Calvary Butte	Daly's averages (1933)		
		Average limburgite	Nephelite basalt	Melilite-Nephelite basalt
SiO_2	40.18	41.25	39.87	37.56
TiO_2	2.66	1.59	1.50	2.66
Al_2O_3	11.70	12.03	13.58	10.08
Fe_2O_3	4.26	5.65	6.71	6.82
FeO	6.68	7.29	6.43	5.94
MnO	0.08	0.54	0.21	0.06
MgO	14.30	11.22	10.46	15.32
CaO	13.28	11.88	12.36	13.82
Na_2O	3.48	3.40	3.85	3.11
K_2O	0.73	1.30	1.87	1.53
H_2O+		3.20	2.22	2.52
H_2O-	1.66			
P_2O_5	0.68	0.65	0.94	0.58
SO_3	0.04			
Cr_2O_3	0.07			
	99.80			
Norm				
ne	15.90			
le	3.49			
an	14.18			
di	33.25			
ol	17.34			
cs	1.55			
mg	6.50			
il	5.17			
mp	1.68			
	99.06			
Mode				
phenocrysts				
olivine	15%			
augite	rare			
biotite	rare			
groundmass				
pyroxene	50%			
plagioclase	rare			
opaque oxides	5%			
interstitial	30%			

A new chemical analysis of the limburgite from Calvary Butte has been made by F. A. Gonyer. It is given in table 3, together with Daly's averages of rock types to which it appears to be related chemically.

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RHEOMORPHIC BRECCIAS*

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ABSTRACT. Igneous intrusive breccias display the well-known features resulting from the injection, crystallization, and reaction of an orthomagma. In contrast to these, many breccias in granitized areas contain undisturbed rock fragments and skialiths surrounded by granitic matrices which exhibit crystalloblastic textures and structures. These are considered to represent an intermediate stage of granitization and have been called replacement breccias.

Other plutonic breccias associated with granitization have crystalloblastic features similar to replacement breccias but differ from them by the presence of fluxion textures. At Cornucopia, Oregon, the matrices of some of these breccias show flow structures. At Sudbury, Ontario, some of the breccia dikes contain fragments which in part appear to merge into a crystalloblastic matrix having a pronounced flow structure. Other breccia dikes in this vicinity are filled with fragments of rocks of various kinds imbedded in a matrix replete with metamorphic minerals showing crystalloblastic features and marked flow alignment.

Breccias formed during metamorphism and exhibiting crystalloblastic features and flow structures cannot be adequately explained as orthomagmatic, but support the interpretation of movement of metamorphosed material. Since the mass flowage of this material can be included, but in a more restricted sense, under the broad definition of rheomorphism, it is suggested that breccias developed under such conditions be termed rheomorphic breccias.

INTRODUCTION

PLUTONIC breccias are of common occurrence in various parts of the world and have been described by many geologists. Interpretations as to the mode of origin of some of these breccias are a simple matter, whereas for others detailed field and petrographic data are necessary. For convenience they may be grouped under three headings: igneous plutonic breccias, replacement breccias, and rheomorphic breccias. The term rheomorphic was used by Backlund (1938) in his discussion of the transformation of quartzite into granite, where he states: "This transformation was accompanied by increase of volume, the quartzites becoming rheomorphic with excellently developed fluidal textures and thereby partly dynamic." Here the term is used as an adjective, in a restricted sense, to imply the mass movement of metasomatic material which had become or had approached a neomagma. Since some

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rheomorphic breccias are very similar to igneous ones and others similar to replacement breccias, the salient features of these two will first be discussed briefly so as to give a basis for comparison.

IGNEOUS PLUTONIC BRECCIAS

Excluding pyroclastic deposits, igneous breccias are found in a wide variety of occurrences ranging from surface flows to all types of intrusive bodies. These breccias are characterized by the presence of angular rock fragments in an igneous matrix. If the fragments consist of rock foreign to the magma they are truly xenoliths; if they represent an earlier chilled phase they are cognate inclusions. In either case the relation of the fragments to the enclosing igneous rock should be such as to show that they were actually engulfed by the magma. This means that relatively simple shapes, which can endure joggling or flowage by the magma, will prevail, whereas bizarre shapes such as irregular fragments connected by thin links would be most unlikely to have survived in such an environment. In an igneous breccia the fragments may exhibit various stages of optalic metamorphism, magmatic reaction effects including evidence of assimilation, or they may not have been affected by the magma.

Perhaps the most significant criterion for the recognition of igneous breccias is the typical igneous character of the matrices which will commonly show intersertal, intergranular or gabbroid textures, and also the tendency toward these textures by the minerals of the early magmatic stage even though partially obscured by late magmatic textures. These earlier high-temperature pyrogenic minerals usually tend to be subhedral or euhedral unless, as in the case of some mafics like olivine, they have been modified by magmatic reaction and thus are merely relics indicative of the well-known reaction series. The overall texture, however, of an igneous matrix will tend to have a regularity of pattern, even though phenocrysts are present, and the grain size will vary in relation to the rate of cooling.

Chilled or finer-grained borders are a characteristic feature if sufficient temperature gradient had existed between the injected magma and the fragments of a breccia. Also under this condition smaller areas of igneous rock will show finer-

grained textures than larger areas, although their mineral composition is similar. Phenocrysts in igneous breccias are usually clear, well formed, and have smooth borders. Included material within the phenocrysts may be glass or earlier-formed pyrogenic minerals. Such included material in plagioclase may show an alignment parallel to crystallographic planes.

The mass movement of magma in an igneous breccia is usually clearly indicated by the flow arrangement of the pyrogenic minerals in the matrix. Such flow structures are particularly noticeable along border zones next to fragments.

REPLACEMENT BRECCIAS

Breccias similar in appearance to some igneous breccias are of common occurrence in the border zones of granitized bodies. This similarity may be so close that a careful scrutiny of field features supplemented by detailed petrographic examination of numerous thin sections is necessary to distinguish them from igneous breccias.

Early stages of the development of some replacement breccias commonly show a crisscross or parallel arrangement of small replacement dikes and veinlets which have been controlled by the jointing in the country rock. In later stages the country rock between the dikes has been so thoroughly transformed and diminished in size by the growth of the replacement dikes that its relics appear as fragments in a breccia.

The earlier stages of other replacement breccias are true brecciated zones consisting chiefly of angular fragments of the country rock with the later feldspathization confined to the fractures between fragments.

Incident to their transformation some of either the pseudo or true fragments, although granitized, may still appear as shadowy relics or skialiths (Goodspeed, 1948), and some may be basified so that they consist chiefly of biotite or hornblende. As might be expected, the fragments in a replacement breccia usually vary in size and are irregular in shape. It is not unusual to find two relatively large fragments joined by a very thin link. Such a feature precludes the possibility of magmatic flowage because the slightest mass movement of the matrix would break the thin connecting link.

Ragged borders of fragments as well as gradational zones with the matrix are common features of replacement breccias.

Occasionally porphyroblasts are seen to extend from a fragment into the matrix (Goodspeed and Coombs, 1937). Porphyroblasts in the fragments are similar to the minerals in the matrix. In the early stages of development there may be noticeable darker borders around the fragments, suggesting an increase in iron as a result of metamorphic differentiation following continued feldspathization. As previously noted, in later stages of development some fragments may be completely feldspathized and others converted into aggregates of hornblende and biotite. Features like this have been described recently by Hsing-Yuan Ma (1948) in his study of the agmatites of Sutherland. In some of the replacement breccias at Cornucopia, Oregon, biotitic aggregates appear to have coalesced to form individual large biotite porphyroblasts. Similar transformations were described by Doris Reynolds (1943) in her studies of the rocks of the Newry Complex.

In the matrices of replacement breccias the texture is not only dominantly crystalloblastic but the overall pattern is typically irregular and uneven with no indication of flow structures. Some replacement breccias have angular open cavities probably inherited from an earlier cataclastic phase (Goodspeed and Fuller, 1944). Such features alone are cogent evidence against the interpretation of an orthomagmatic mode of origin.

Some replacement breccias record an early advancing stage of static granitization; others an intermediate stage; and a few a later retrogressive stage, such as the replacement aplite breccia of Cornucopia (Goodspeed and Fuller, 1944). In advanced stages of granitization the fragments become more completely transformed and the characteristic brecciated appearance tends to become obliterated so that only shadowy outlines of the fragments remain in the granitized rock. In this stage these breccias can be considered static migmatites. Whether replacement breccias represent an earlier stage of incipient granitization or a later more complete stage, their matrices do not show flow structures nor do the fragments suggest any dislocation such as would be expected by the mass movement of a magma.

MOBILIZED AND RHEOMORPHIC BRECCIAS

Some breccias that exhibit most of the features just described differ in one respect, that is, they locally show evidence

PLATE 1

Fig. 1. Plane light.

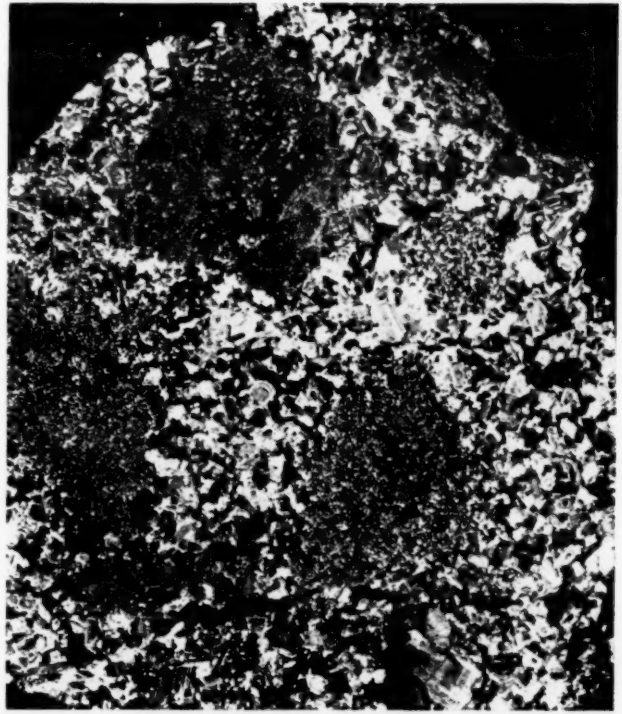

Fig. 2. Crossed nicols.

Photographs of a 3¼ x 4 inch thin section. Replacement breccia from the Bonanza Basin, Cornucopia, Oregon. Note (plane light) a slight alignment of mafics indicative of incipient mobilization, and (crossed nicols) the typical irregular crystalloblastic texture of matrix.

PLATE 2

Plane light. Photograph of a 3¼ x 4 inch section of a partially mobilized replacement breccia from above the Red Jacket workings, Cornucopia, Oregon. Note alignment of mafics shown in left part of matrix.

PLATE 3

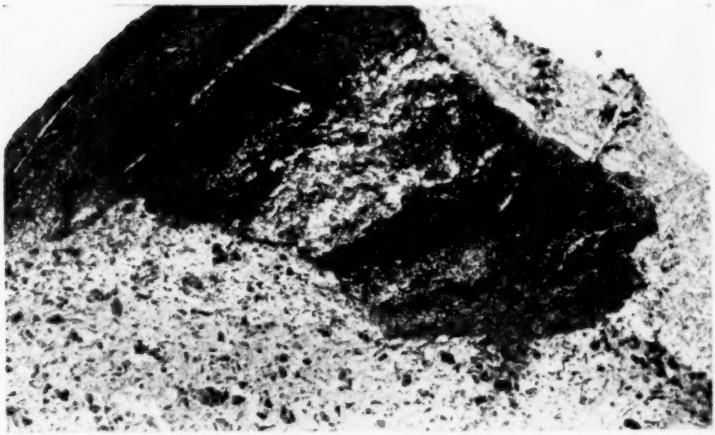

Fig. 1. Plane light. Photograph of a 3¼ x 4 inch thin section of a rheomorphic breccia from near the Red Jacket workings, Cornucopia, Oregon. Note the flow structure and the euhedralism of some of the minerals in the left part of section in contrast to the earlier replacement features of the matrix in the lower right part of matrix.

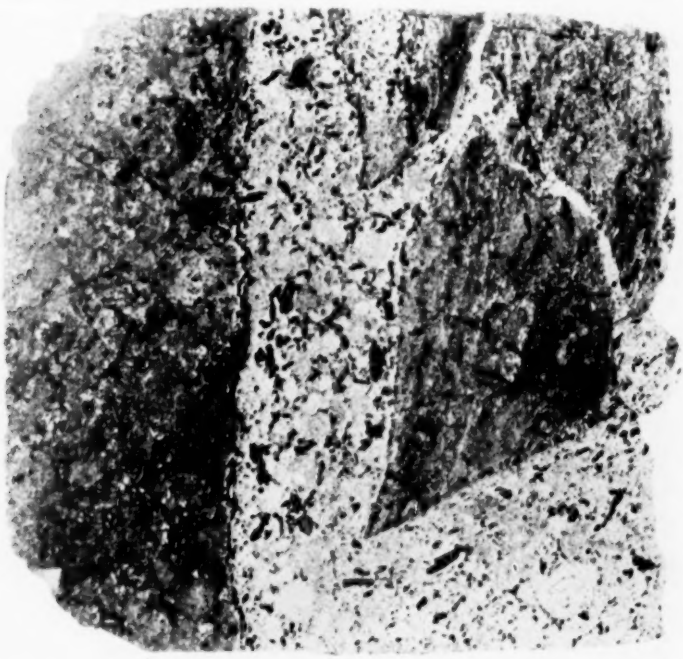

Fig. 2. Plane light. Photograph of a 2 x 2 inch thin section of a partially mobilized replacement breccia from above the old Union Camp, Cornucopia, Oregon. Note the alignment of mafic minerals in the lower right part of the matrix.

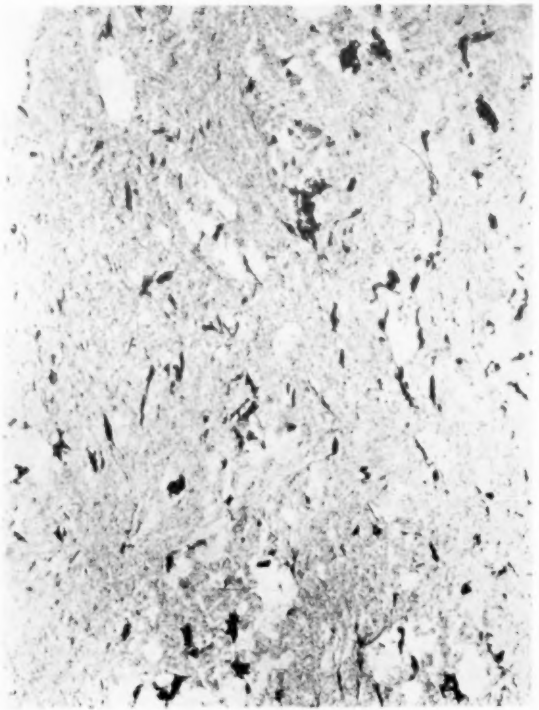

Fig. 1. Plane light.

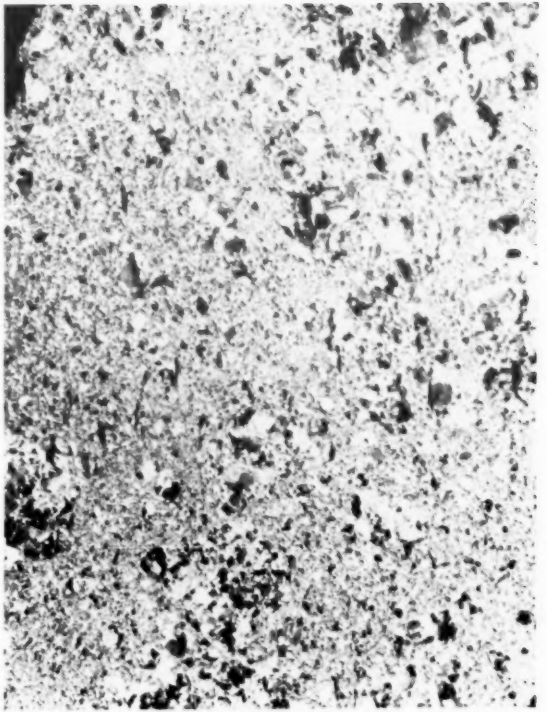

Fig. 2. Crossed nicols.

Photographs of a 3¼ x 4 inch thin section from a rheomorphic breccia exposed in the Clark extension adit at Cornucopia. Note cataclastic and flow structure, and crystalloblastic texture.

of flowage. This appears as a flow alignment of elongated minerals in their matrices, indicating that sufficient heat was available under differential pressure conditions to permit local mobilization in a partially metasomatized mass. Under continued intensity of granitization some mobilized replacement breccias show still more evidence of flowage not only in their matrices but also by the dislocation of their relict fragments. It is also noticeable that crystals which have formed in such a mobile mass tend to be euhedral. These breccias are called rheomorphic breccias so as to differentiate them from static replacement breccias or from those of orthomagmatic origin.

At Cornucopia, Oregon, most of the rheomorphic breccias are found in the contact zones of hornfels and granodioritic rock. They are commonly of irregular lenticular shape and range in size from 500 to 600 feet in length and 50 to 100 feet in width. Steeply dipping contacts which are usually gradational into feldspathized schistose hornfels or previously granitized rock are common. The longer dimension of these breccias is roughly parallel to the general hornfels-granodioritic contacts.

Angular fragments in these breccias vary in size from a fraction of an inch to several inches in diameter, and exhibit both ragged and sharp borders. Fragments of hornfels show varying degrees of transformation with little change in the incipient stages to complete recrystallization, either feldspathization or basification, in the later stages (plate 1, fig. 1). The grade of metamorphism, however, does not exceed that of the mesozonal facies. Fragments of granitic rock show no appreciable change, and are more homogeneous than the hornfels fragments. They are identical to some of the phases of the earlier granitized rock of larger adjacent masses.

The matrices of these breccias vary widely in both mineral composition and texture. Some are chiefly aggregates of quartz and feldspar with subordinate biotite and hornblende; others are rich in mafics and are dioritic in composition. Textures vary from coarse to fine-grained but are characterized by the presence of ubiquitous fluxion textures. Many of the matrices have a porphyritic appearance with larger crystals of feldspar (usually plagioclase) set in a very much finer-grained groundmass. In some breccias many of the larger crystals of the matrices clearly show features of early por-

phyroblastic origin, such as sieve structures and the inclusion of earlier-formed metamorphic minerals. Some of the larger crystals, however, are quite similar to phenocrysts of an orthomagmatic rock, since they are clear, free from inclusions, and are euhedral.

Many of these breccias from Cornucopia, Oregon display small-scale variations in both fragments and matrices even within the area of a large thin section, 2 x 2 or 3¼ x 4 inches. The preparation of such sections has been described recently by Lang and Smedes (1951). For example, within a single section may be seen some fragments with gradational and basified borders, features characteristic of replacement breccias. Other fragments in the same section have sharp contacts with no crystalloblastic penetration of the matrix. In some parts of the matrix the crystalloblastic aggregate is directionless without the slightest indication of flow structure. In other parts of the matrix distinct flowage is indicated by a rough alignment of feldspar and hornblende and by the fine pattern of flakes of biotite which appear to have swirled around schistose fragments irrespective of the orientation of their structure (plate 2 and plate 3, fig. 1).

One of the breccias at Cornucopia showing these features outcrops a few hundred feet above the old workings of the Red Jacket mine. It has the shape of a thick lens 250 by 150 feet and has gradational contacts with the surrounding rocks which are in part a schistose hornfels and in part a fine-grained leucocratic granitic rock. Where small (less than 1 inch) fragments are dominant, this breccia is lighter in color than where larger fragments are abundant, because the smaller fragments are more completely granitized than the larger ones. Many fragments contain porphyroblasts in various stages of development ranging from incipient amoeba-like forms to subhedral crystals. These porphyroblasts exhibit the usual features of crystalloblastic growth, such as sieve or poikoblastic structure with turbid centers due to minute included metamorphic minerals, crenulated borders, compositional changes shown by zoning and glomeroblastic aggregates. Progressive zoning is especially common, and where a plagioclase porphyroblast straddles the border of a fragment, that part of the crystal which surrounds and includes the mafic minerals of the fragment is likely to be much more calcic

(labradorite) than the part in contact with the matrix or even extending into it. This part of the porphyroblast may be close to albite in composition. The boundaries between the zones of these porphyroblasts are commonly hazy and indistinct.

A noticeable feature of this breccia is the presence of scattered angular and subangular cavities from 1 cm to 2 cm in diameter. Remnants of partially decomposed fragments in some of the cavities suggest that locally solution exceeded precipitation during replacement. Iron staining in some of the cavities is no doubt due to the oxidation of pyrite, a common but minor mineral in many of the Cornucopia breccias. The lining of some of the cavities includes actinolite, limonitic material, white garnet, and feldspar. With the exception of a few small specks of limonite the matrix surrounding the cavities is unaltered, quite hard and compact.

The granitic matrix of this breccia varies in mineral composition according to the thoroughness of granitization, but in general it is that of a quartz diorite with 70 per cent plagioclase, 15 per cent quartz, 10 per cent hornblende, and 5 per cent biotite and with minor accessories which include magnetite, apatite, epidote, chlorite, and zoisite. The texture of the granitic matrix is typically crystalloblastic with an uneven overall pattern and sutured intergrowths. Where larger plagioclase crystals are present they are identical to the porphyroblasts found in the fragments. The matrix of some parts of the breccia is devoid of any flow alignment of crystals, but in other parts marked flow structure of the mafic minerals is present. From these features it may be interpreted that part of the breccia represents earlier static replacement and that other parts indicate later mobilization.

Additional evidence with regard to mobilization in this breccia is shown by a rather unique feature. Transecting the breccia parallel to its longer axis is a two-foot porphyry dike with contacts that are in part gradational and in part sharp. In large (3¼ x 4 inches) thin sections cut across the gradational part of the contact of the dike with the breccia, the delicate flow features of the matrix can be seen to merge into those of groundmass of the dike. The streamlined pattern of swirls of minute crystals of biotite and hornblende around larger plagioclase crystals indicates that the flowage

was from the matrix of the breccia into the dike. Marked flow structures are noticeable in the groundmass of the dikes where the flow alignment becomes parallel to the wall of the dike. Many of the larger crystals in the dike, especially the plagioclases, are similar to the porphyroblasts in the matrix of the breccia and like them exhibit features indicative of crystalloblastic growth. Some of the larger hornblende crystals, however, are homogeneous and well formed, thus resembling phenocrysts of igneous derivation. They appear to have been formed by fractional crystallization from the mobile material in the dike. Hence this porphyry dike has been termed a rheomorphic dike because it not only records the flowage of metasomatized material but also shows a later separation of crystal in a manner similar to the crystallization of a magma (Goodspeed, 1952). Such newly formed magmatic material has been termed neomagma (Goodspeed, 1939).

Another example of mobilized breccia at Cornucopia is exposed in one of the long upper adits (Clark extension) about 100 feet west of a previously described replacement aplite breccia (Goodspeed and Fuller, 1944). This mobilized breccia is well within the quartz dioritic rock of the Cornucopia "stock," being about 1 mile west of the main hornfels-granitic contact and approximately 2000 feet below the surface. Here the quartz diorite consists of a crystalloblastic aggregate of plagioclase (andesine), quartz, and biotite and displays the same uneven pattern that characterizes the granitized rocks of the contact zone.

This breccia is a steeply dipping tabular mass a few feet thick with no definite walls, no slickensides, and no gouge. It consists chiefly of angular and lenticular fragments of quartz diorite with a few fragments of aplite imbedded in a much finer-grained slightly darker-colored matrix in which the mafics show an apparent flow alignment. A few small irregular open cavities are also present in the matrix.

Large thin sections of this breccia show cataclastic structures: angular fragments of quartz diorite, porphyroclasts of plagioclase and quartz, and a groundmass which varies in grain size from a cataclasite to a mylonite. The quartz diorite fragments, similar to the country rock, are relatively coarse-grained crystalloblastic aggregates of plagioclase An_{31} with some quartz and biotite. Bent plagioclase crystals are notice-

able along the borders of a few of the fragments. Some smaller fragments have a drawn-out appearance and consist of aggregates of white garnet, biotite, magnetite, and epidote. In addition to the pronounced cataclastic structure of the matrix, this breccia exhibits distinct crystalloblastic features. Some of the minutely brecciated plagioclase porphyroclasts have been completely healed by a later growth of feldspar, producing an irregular mosaic pattern. Most of the smaller mineral grains in the groundmass show later crystalloblastic growth, as is evidenced by finely crenulated borders and intricate interlocking aggregates. The matrix is slightly richer in biotite than the quartz diorite fragments, and drawn-out flakes of biotite show alignment and are in swirls around the fragments and porphyroblasts (plate 4).

Although it is evident that cataclasis played a dominant role, at least initially, in the formation of this breccia and would explain some of the structures, this is not a simple cataclastic zone, for there is distinctly later crystalloblastic growth and also marked flow structures around fragments. Furthermore, the breccia contains fragments of aplite, a rock that is not present in the granitic wall immediately adjacent to the breccia. Therefore it is inferred that the original cataclastic zone, subjected to continued increase of pressure and penetration by hot solutions, became mobilized under conditions favorable to later crystalloblastic growth. Like many other examples of mobilization and rheomorphism at Cornucopia, this breccia postdated the main period of granitization, although it is one of the results of the late pre-Tertiary metamorphism.

Some cataclastic flow breccias, however, appear to have been formed during the advancing stage of granitization. One of these, at Cornucopia, is exposed for a few feet along the north bank of Pine Creek near the former site of the Queen of the West mill. It is in the main contact zone of the granodiorite mass of Cornucopia Mountain and the schistose hornfelses of Red Mountain, a zone replete with replacement breccias and replacement dikes. Here the breccia consists of angular subangular and elongated fragments of schistose hornfels with numerous irregular aggregates of quartz and feldspar in a dark-colored fine-grained matrix. Veinlets of feldspar and quartz are roughly parallel to the main granitic hornfels

contact; feldspar crystals are scattered throughout the matrix and are concentrated along the borders of some of the hornfels fragments (plate 5).

Large thin sections of this breccia show that the hornfels fragments are in various stages of feldspathization, ranging from an incipient crystalloblastic stage with much hornfels material present and anhedral plagioclase feldspars filled with inclusions, through an intermediate porphyroblastic one with some larger better-formed, clearer feldspar and less hornfelsic material, to a completely recrystallized crystalloblastic aggregate of feldspar, quartz, and brown biotite. The groundmass consists chiefly of a fine-grained aggregate of biotite, feldspar, and quartz. Although cataclastic structures are prominent, the arrangement of the biotite is strongly suggestive of flowage. The presence of some intergranular myrmekitic intergrowths is indicative of action by later solutions.

The formation of this breccia can be interpreted as being due to the essentially concomitant action of cataclasis, plastic flow, and metasomatic replacement. In this breccia the hornfels fragments show marked effects of cataclasis and there is also some fragmentation of the crystalloblastic feldspar-quartz-biotite aggregates. Cataclasis alone seems to be an inadequate explanation for the flow structures in the matrix. Plastic flow, however, in addition to cataclasis is a plausible interpretation for their origin. A similar combination of cataclastic deformation and plastic flow with associated crystalloblastic growth and with metasomatic feldspathization continuing after the end of movement in dike-like mobilized zones traversing the migmatitic gneisses of the Northern Cascades of Washington has been described by Misch (1952). With respect to these he has used the term cataclastic-plastic flow.

Rheomorphic breccias are by no means an exceptional feature unique to Cornucopia, Oregon, as may be demonstrated by a brief description of two other typical occurrences, one in the Northern Cascades of Washington and the other at Sudbury, Ontario.

Many other examples of mobilization and rheomorphism have been recognized by Misch (1949) in his geological investigations in Okanogan County in north-central Washington. He recently noted an excellent example of a rheomorphic brec-

cia in the northern Cascade Mountains of Washington.[1] Concerning the regional setting he states: "This area consists of migmatitic gneisses which have been formed by synkinematic metasomatic granitization of schists and amphibolites and which contain numerous remnants of these rocks. After the end of regional deformation, some metasomatism has continued under static conditions, forming various replacement veins and patches. Static replacement has been locally accompanied and succeeded by small-scale mobilization, usually started by localized plastic but essentially still crystalline material. In some cases the mobilized material has the character of a plastically deformed replacement breccia. In many instances metasomatic feldspathization has continued after the intrusion of mobilized dikes." Misch has photographed a glaciated outcrop of the contact of one of these breccias with biotite schist (plate 6).

At Sudbury, Ontario, there are numerous occurrences of breccias some of which are called intrusive because they occur in dike-like forms and display distinct flowage features. They have recently been described by Fairbairn and Robson (1941, 1942), Cooke (1948), and Yates (1948). The writer wishes to acknowledge the aid of Frank Zurbrigg, Chief Geologist for the International Nickel Company, and Victor C. Clausen, who during the summer of 1948 conducted him to critical field exposures at Sudbury. He is also further indebted to Dr. Clausen for the use of many diagnostic specimens and thin sections. The Sudbury intrusive breccias occur in steeply dipping or nearly vertical dike-like masses up to several miles in length and varying in width from a few feet to 1 mile. Field relations clearly indicate that they are later than the Sudbury noritic intrusive or its metamorphosed facies and other Precambrian rocks, except some late olivine diabase dikes which locally transect them.

Perhaps the most amazing feature of these breccias is the variation in the size, shape, and rock types of their fragments. Concerning the Frood breccia, Yates (1948) stated: "It possesses all the physical characteristics of an intrusive breccia, carrying fragments and inclusions of all sizes from microscopic to as great as 3000 feet in length and 1000 feet in width. The fragments are almost always rounded but do

[1] Personal communication.

not appear to have been carried far, for most of them are from the adjacent or nearby wall-rocks." Some of the fragments of this breccia are a quartz diorite breccia which in itself is apparently a replacement breccia. One outcrop in a road cut a few miles north of Sudbury on the highway to Capreol affords a small horizontal and vertical exposure of the Frood breccia. The glaciated surface shows the variation in size and shape of the fragments, some of which are drawn out and merge into the matrix (plate 6, fig. 2). Among the rounded, irregular fragments in the vertical exposure is a lenticular one of quartz diorite about 2 feet long and 1 foot wide. One-half of this fragment parallel to its longer axis has a hazy outline grading into the matrix of the breccia which shows flow structure.

This indicates not only metamorphism of the fragment but also incipient mobilization. Metasomatism of fragments in the Sudbury intrusive breccias has been noted by Fairbairn and Robson (1941) who state that: "The margins of the fragments are in places richer in hydroxyl minerals than the center."

With regard to the matrix of these breccias Yates (1938) stated:

"The matrix varies considerably, but has some relation to the rocks through which the breccia passes. In areas of granite or quartzite the matrix is light gray whereas in gabbros and greenstones it is dark green to almost black. A study of a great many thin sections gives the following estimate of composition: 3-50 per cent hornblende—a blue-green variety with an exinction angle of 20 degrees, 5-20 per cent biotite, 5-20 per cent quartz, 5-20 per cent oligoclase, 0-10 per cent orthoclase and microcline with some albite, 0-2 per cent sphene, 1-3 per cent metallics, and 0-3 per cent chlorite, epidote, calcite, and clinozoisite. In some cases the matrix is almost entirely fine granular quartz and one was noted with 60 per cent quartz and 40 per cent augite in a fine granular aggregate.

"The matrix is pretty surely controlled by the composition of the inclusions but the heterogeneity of the inclusions gives rise to an extremely variable and complex matrix. It cannot be an igneous rock in the strict sense of the word. There is no euhedralism of any of the minerals, nor order of crystallization is apparent, and there is a lack of homogeneity. The

PLATE 5

Breccia just below bridge crossing Pine Creek near the former site of the Queen of the West mill.

PLATE 6

Fig. 1. Rheomorphic breccia in contact with biotite schist from south side of McMillan Spire in northern Cascade Mountains of Washington. Note the evidence of flowage in breccia in contrast to the static replacement dike shown at bottom of photograph. (Photograph by Peter Misch.)

Fig. 2. Frood breccia a few miles north of Sudbury on the highway to Capreol. (Photograph by Victor C. Clausen.)

composition in some cases is unique, for instance, the one composed of 60 per cent quartz and 40 per cent augite. Evidences of recrystallization are shown in nearly every section."

The matrices of these breccias are in general finer grained than the fragments and display pronounced flow structure. Fairbairn and Robson (1941) state that: "Sinuous layers of mica flakes oriented parallel to walls and fragments are typical. The mica occurs also in swirls and small folds, and there is commonly a compositional banding of alternate mica-rich and mica-poor layers. Small breccia veins, which in many cases appear to be isolated from larger feeders, evidently possessed the ability to penetrate into small crevices." In several large thin sections the matrices are seen to consist of a fine-grained, in some cases an extremely fine-grained, aggregate of biotite, hornblende, quartz, epidote, chlorite, and feldspar in varying proportions. Microcataclastic structures, crystalloblastic textures, and distinct flow alignment are particularly noticeable.

Continued cataclasis in some of the Sudbury breccias locally produced minute shear and fracture planes which afforded openings for the introduction of hydrothermal solutions carrying sulphides. Where present, the sulphides, dominantly pyrrhotite with pentlandite and chalcopyrite, replace the fragments and matrix of the breccias. The breccia dikes were formed later, and probably much later, than the Sudbury noritic intrusive, as, for example, on the North Range in the vicinity of the Levack Mine the breccia intrudes the base of the Norite Intrusion for hundreds of feet (Clausen, 1947). Therefore the origin of these sulphides cannot be attributed to magmatic segregation from the noritic magma. Because the breccia dikes are major structural features miles in length it seems quite plausible to suggest that the metallization came from a deep, perhaps a very deep source. The presence of heavy elements such as platinum and iridium also favors this suggestion.

In contrast to some of the mobilized and rheomorphic breccias at Cornucopia, Oregon, the Sudbury breccias appear to have been intruded at a low temperature as is indicated by their mineral composition. However, they can be included in the same category as the previously described breccias not only

because mass flowage of metamorphosed material is evident but also because concomitant crystallization is indicated.

CONCLUSIONS

Igneous plutonic breccias are commonly contact facies of an intrusive body, and their matrices, although usually finer-grained, will have a mineral composition similar to the parent magma. Their fragments may show the effects of high-grade thermal metamorphism which is so common along intrusive contacts. These breccias indicate that magmatic stoping played a role, although perhaps a minor one, in the emplacement of the intrusive mass.

Some replacement breccias occurring along the border zones of granitized masses are features of large-scale static metasomatism and illustrate one of the mechanisms for the advance of granitization. The mineral composition and textural pattern of the matrices of contact replacement breccias are characterized by wide variations. For example, in a single large specimen of a contact replacement breccia petrographic types of the matrix may range from diorite, diorite porphyry, quartz diorite, to aplite and pegmatite, whereas away from the contact the large granitized mass may be predominantly quartz diorite. Relict fragments in a replacement breccia commonly display all stages of metasomatic replacement, from those slightly feldspathized to completely granitized skialiths. Effects of metamorphic differentiation are also common, some fragments may be changed to an aggregate of biotite or hornblende. They do not, however, show the effects of high-grade thermal metamorphism.

Many mobilized and rheomorphic breccias are similar to replacement breccias, since they have been derived from them during a later stage of granitization. They exhibit features indicative of plastic flow and of a sufficient amount of intergranular fluid to allow some minerals to form by fractional crystallization during the period of flowage. Although flow structures and later-formed crystals in rheomorphic breccias may produce a similarity to igneous plutonic breccias, the presence of earlier minerals exhibiting crystalloblastic features and the absence of well-formed earlier pyrogenic minerals, their relics, or orthomagmatic textures serve to distinguish them from truly igneous breccias.

TABLE 1

Comparison of Petrographic Features of Igneous Plutonic Breccias, Replacement Breccias, and Rheomorphic Breccias

Igneous	*Replacement*	*Rheomorphic*
1. Fragments are usually angular with shapes which can endure magmatic flow.	Bizarre-shaped fragments with thin connecting links are common.	Angular and rounded fragments of simple shapes compatible to movement of neomagma.
2. Fragments disturbed by magmatic flow.	Fragments undisturbed.	Fragments drawn out by plastic flow.
3. Optalic, thermal, or deuteric metamorphism of fragments may be noticeable.	Various stages of feldspathization common.	Many fragments similar to those of replacement breccias. Some show evidence of later metasomatism.
4. Larger crystals in matrix are typical phenocrysts, usually well formed.	Matrix contains typical porphyroblasts which commonly exhibit various stages of development showing characteristic features such as crenulated borders, sieve structures and turbidity due to inclusion of minute metamorphic minerals.	Some larger crystals in matrix may show indications of earlier porphyroblastic development. Others are similar to phenocrysts.
5. Flow structures in matrix are common.	No flow structures are present in the matrix.	Matrix usually shows flow structures.
6. Chilled or finer-grained borders against fragments are common.	No chilled or finer-grained borders against fragments.	Usually no chilled or finer-grained borders against fragments.
7. Typical igneous textures in matrix with tendency toward overall uniformity.	Matrix shows crystalloblastic textures commonly with an uneven overall pattern.	Earlier formed crystalloblastic textures are usually prominent in matrix.
8. Matrix consists chiefly of high-temperature minerals with low-temperature minerals limited to deuteric alteration.	Contemporaneous low-temperature minerals are usually conspicuous in the matrix.	Mineral composition of matrix usually similar to that of replacement breccias. Minerals showing igneous characteristics, if present, are distinctly later in origin.

A comparison of some of the petrographic features of igneous plutonic breccias, replacement breccias, and rheomorphic breccias is given in the accompanying tabulation (table 1). Since any of these breccias may occur in the border zone of a plutonic rock body, their recognition is of utmost importance to the problem of the mode of origin of the adjacent plutonic mass. Detailed field and petrographic data are necessary for an adequate interpretation of the mode of origin of these breccias. Intrusive relationships and flow structures by themselves alone do not necessarily mean an orthomagmatic derivation.

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DISCUSSION

The paper by F. R. Haeberle entitled "Coral Reefs of the Loyalty Islands" (this JOURNAL, vol. 250, September 1952) suggests the following comments:

1. The tilt of Ouvéa Island was mentioned long ago by the French mining engineer and geologist J. Garnier (1867, p. 5). With respect to the upheaval and tilting from SE to NW of the whole Loyalty group one must recall the idea expressed by Davis (1925) and confirmed by the present author (Routhier, 1952*a*) of a longitudinal warping of New Caledonia or "Grande Terre" (second cycle). This warping would have played anew during the sinking that opened the third cycle. It would explain that on the west coast the drowning would have been stronger in the north and south ends of the island than in the median part.

2. By announcing that the core of Maré Island is made of serpentine, Haeberle (pp. 656, 658, 663-664, 666) necessarily suggests the existence of an ultramafic ridge, similar to the great New Caledonian peridotic masses and parallel to the "Grande Terre." This possibility is worthy of consideration by geotectonicians.

Now, we must expressly question the existence of serpentine on Maré. This island was visited by numerous inhabitants of New Caledonia, to whom serpentine is a very familiar rock. Moreover, it has long been known that central knolls of Maré (Rawa and Peorawa) are made of volcanic rocks, not of serpentine. Pointed out without petrographic precision by Grundemann (1870, p. 365), identified as olivine basalt by Sarasin (1914, pp. 234-235), these rocks were studied by Lacroix (1918, 1940). They correspond to olivine basalt, doleritic olivine-poor basalt, pegmatitoid dolerite.

It is noteworthy that these three rocks belong to Lacroix's "β" type, whereas Paleogene basalts known on the Grande Terre belong to "α" type (Routhier, 1952*a*, 1952*b*). It might be possible to find there a confirmation of Lacroix's idea (1918) that these basaltic rocks are not very old, perhaps contemporaneous with those of the New Hebrides. Sarasin (1917, p. 264) claimed that Loyalty limestones were mostly of an "old-Terti-

ary" age; but micropaleontologic determinations, on which this claim was based, should be carefully rechecked.

Nevertheless, the Loyalty Islands may be located along a line of volcanic activity whose age is not known but probably is younger than the most recent extrusions on the Grande Terre.

In any case, it must be strongly emphasized that in the materials studied by Lacroix there was no peridotite or serpentine. Collectors of these materials, notably M. Leenhardt, then Le Chartier de Sédouy, at that time chief of the New Caledonia Mines Department, could hardly have overlooked ultramafic rock in outcrops, the largest of which does not exceed 500 meters in length.

At any rate, and primarily because of the lack of confirmatory samples, which Haeberle states were lost (p. 658), it seems premature to assume that the Loyalty coral formations rest on serpentine. Accordingly, any geotectonic speculation based on such a statement is open to serious question.

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REPLY

The comments of M. Pierre Routhier were read with interest by this author. There seems to be no question that the entire Loyalty Island block has been uplifted, or has undergone some form of longitudinal warping. This warping does not seem to have been uniform throughout the entire block, however. The Astrolobe Reefs, on the north, are separated from Heo Atoll by a distance of 29 miles with a maximum difference in altitude of less than 20 feet between the two. Ouvéa Atoll is 15 miles south of Heo, and the maximum difference between the highest altitudes is 30 feet. The island of Lifu is 27 miles south of Ouvéa, but the difference between points of highest altitude is 130 feet. Thus, the distance between Lifu and Ouvéa is not quite twice the distance between Ouvéa and Heo, but the altitude differences are over four times as great. Maré lies 25 miles south of Lifu with a maximum altitude of 140 feet higher than Lifu. Maré, then, lies approximately the same distance south of Lifu as Ouvéa does north, whereas the difference in altitude is about the same. As a result, the author believes that the entire block was uplifted, with the largest amount of uplifting taking place at the southeast end of the group. As the uplift is not uniform throughout the entire block, it was suggested that faulting occurred normal to the main axis of the uplift, permitting more or less uplift in different sections.

It is indeed unfortunate that no samples of the core material of Maré are available for modern thin-section study. Whereas Davis (1925, p. 10) merely states that the core material is *compact* volcanic rock, Compton (1917, p. 88) states definitely that it is serpentine. The author freely admits the possibility that this core material has a composition other than serpentine. However, he spent considerable time attempting to distinguish, by eye, samples taken at Maré from those of New Caledonia, without being able to do so. Several residents of New Caledonia, familiar with both islands, were also unable to distinguish between the samples. As no mention of basalt on New Caledonia has been made prior to M. Routhier's paper, it would seem safe to assume that it is not common and probably occurs only in small areas, whereas it is far from uncommon in the New Hebrides Islands. It is suggested that a study of the

surrounding sea floor may be of some assistance. The Loyalty Islands are separated from New Caledonia by a relatively flat-bottomed trench, 60 miles wide with maximum depths of about 7000 feet. The New Hebrides Islands are 110 miles northeast of the Loyalty group and depths of over 22,000 feet are common between them. West of New Caledonia, the ocean bottom falls off rapidly to depths of over 12,000 feet. It would seem that New Caledonia and the Loyalty Islands group represent two parallel blocks rising from ocean floor, separated by a comparatively shallow trough. On either side of these two blocks the ocean floor is far deeper than in the trough between the two blocks. Separated from the Loyalty Islands by a deep, wide trough are the New Hebrides Islands. It would seem to the author that the age and composition of the island blocks of New Caledonia and the Loyalty group would be more like each other than the age and composition of the Loyalty Islands and the New Hebrides. It is not meant to infer that the entire New Caledonian block is composed solely of serpentine. Much more information on the entire area is necessary before it may be stated that the composition of the Loyalty Islands is more closely allied to that of the New Hebrides than to New Caledonia.

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REVIEWS

Radio Astronomy; by BERNARD LOVELL and J. A. CLEGG. Pp. 238; 128 figs. New York, 1952 (John Wiley & Sons, $4.00).—The authors are among the most active workers in the new and rapidly developing field of radio astronomy, and so are unusually qualified to write this first survey of it. The common difficulty with a new science formed by the cross-fertilization of two previously separate disciplines is that its literature is in an unfamiliar idiom to those raised on one of these disciplines only. Recognizing this, the authors commence with a brief but useful précis of the relevant astronomical fundamentals for radio engineers, and an outline of radar and the theory of radio noise measurements for astronomers.

Seven chapters treat meteors, covering daylight meteor streams discovered by radio techniques, and the measurement and interpretation of meteor velocities. The important conclusion is demonstrated that the radar velocity measurements show no evidence for any meteors of interstellar origin. Next radio emission from the sun is considered, and the enormous outbursts of radio noise from sunspots and solar flares are described. Thirty pages are devoted to radio noise from the Galaxy and from extragalactic sources, and to radio stars.

The novelty of the subject has forced the viewpoint of the book to be primarily observational rather than theoretical. Style and content of the book are excellent. A second edition seems already required by the very rapid growth of radio astronomy, as even the brief interval since publication has been marked by the discovery of the 21 cm galactic emission line of hydrogen, by new identifications of radio stars, and by the investigation of Dutch workers on galactic radio noise. JOSEPH ASHBROOK

Theoretical Nuclear Physics; by JOHN M. BLATT and VICTOR F. WEISSKOPF. Pp. xiv, 864; numerous figs. New York, 1952 (John Wiley & Sons, Inc., $12.50).—Factual knowledge about nuclei and nuclear phenomena has accumulated at an enormous rate during the last two decades, and many published collations, both encyclopedic and systematic, cover this wide and rambling field. Such material, however, carries within it only a modicum of rationale and suggests but little in the way of fundamental understanding. The slowness with which nuclear physics is yielding to embracive and illuminating principles is in fact astonishing when judged against theoretical progress in related fields. For this reason the absence of comprehensive treatments of nuclear theory hitherto is not surprising.

The same considerations reveal the magnitude of the venture which the volume here reviewed undertakes. Fully aware of the difficulty of their task, the authors set their sights with modesty: they limit themselves to an "investigation and correlation of known

nuclear properties on a semi-empirical basis." To name the contents of the book would lengthen this review unduly; the reader may gain a fair appraisal of its scope if we list the major items that have been omitted. They are: cosmic ray and meson physics, neutron optics, magnetic resonance, and meson field theories.

The treatment presupposes acquaintance with the quantum theory and a general knowledge of nuclear experimental facts. Yet it does not leave theoretical results uninterpreted and makes abundant reference to illustrative experimental work. Its proofs tend to be elegant rather than didactic; they have an appeal to the theorist working in the field as well as to the discerning graduate student. The professional caliber of the authors is ample guarantee for the authoritative qualities of the work. It is, in this reviewer's opinion, a monumental summary of the best that is available in this area of research. HENRY MARGENAU

The Nature of Some of Our Physical Concepts; by P. W. BRIDGMAN. Pp. 64; 4 figs. New York, 1952 (Philosophical Library, $2.75).—In this book are reprinted three lectures delivered at the University of London by Professor Bridgman in 1950. The basic subject matter for the lectures is taken from three of Bridgman's books: *The Logic of Modern Physics, The Nature of Thermodynamics,* and *The Thermodynamics of Electrical Phenomena in Metals.*

The first lecture summarizes the philosophy of the operational approach. This viewpoint is illustrated by a comparison of the field concept with that of action at a distance, with particular attention being given to their instrumental indistinguishability.

An analysis of the fundamental concepts of thermodynamics is presented in the second lecture. Especially interesting is the careful treatment given to the problem of extending the range of thermodynamics to include irreversible processes.

The final lecture is concerned chiefly with the application of the ideas expounded in the preceding lectures to the specific problem of thermoelectric phenomena.

Throughout the book the author emphasizes that the development of a physical theory is characterized by a progressive weaving together of verbal operations with instrumental operations. Professor Bridgman has succeeded in presenting within the confines of three lectures a convincing well-integrated description of the nature of this weaving process. A. A. EVETT

Principles of Quantum Mechanics; by W. V. HOUSTON. Pp. vii, 288. New York, 1951 (McGraw-Hill Book Company Inc., $6.00).—More than fifteen years' personal teaching experience in quantum

mechanics has been applied by Professor Houston to this introductory text, and the book shows clearly the benefit of being developed under conditions in which it is intended to be used. Professor Houston has chosen to deal exclusively with the Schroedinger method throughout the text. He believes that an introductory course should encourage the student to attain considerable proficiency in the use of one method rather than to achieve a lesser degree of competence in a number of alternate methods.

The first two chapters consist of background material. The Hamiltonian formulation of classical mechanics is briefly summarized, and several of the experiments which indicate the inadequacy of classical mechanics are discussed.

Following these preparatory chapters, the author begins the formulation of the logical structure of quantum mechanics. A set of postulates from which nonrelativistic wave mechanics can be derived deductively is presented. As the consequences of the postulates are examined, the physical implications are kept in the foreground. The establishment of the logical framework is followed by chapters on the central field problem, approximate methods, and the Pauli exclusion principle.

Application of wave mechanics to spectroscopy, collision problems, electrons in solids, and electromagnetic radiation occupies the last two-thirds of the book. The spectroscopy section contains a very thorough treatment of hydrogen-like spectra and two-electron systems. A brief survey of quantum statistical mechanics is included in the skillfully presented section on electrons in solids.

This text is designed primarily for the student whose interest in quantum mechanics is derived from the fact that it is a practical weapon for attacking practical physical problems. Consequently, the author has avoided discussion of the semi-philosophical aspects of the subject and has concentrated on presenting quantum mechanics in a manner which quickly and coherently brings the student to grips with applications. Such an approach will probably be greeted with a friendly response from instructors of introductory courses in quantum mechanics. A. A. EVETT

Trattato di Geologia; by Ramiro Fabiani. Pp. 744; 756 figs. Rome, 1952 (Istituto Grafico Tiberino, *l* 8,800).—Although new textbooks of general geology appear in America with great and increasing frequency, a new text from any part of Europe is an uncommon occurrence, and specifically, an Italian one is a real rarity. This new volume, whose author is Professor of Geology in the University of Rome, is authoritative, comprehensive, and readable.

Although intended primarily for Italian-speaking university students, the book will be useful to non-Italian geologists as a reference to the localities of occurrence of stratigraphic units in Italy. In this respect Professor Fabiani's text is a most useful accompaniment to the fourth edition of Gignoux' *Geologie Stratigraphique* (1950).

However, the present volume is far from being a stratigraphic catalog. It is a balanced introduction to Geology, divided into four parts: Lithology (20 per cent of the whole text), Structural geology (12 per cent), Stratigraphy (40 per cent) and Petroleum geology (25 per cent). The unusual emphasis on the geology of oil is doubtless attributable to the fact that the petroleum industry today absorbs most of the young geologists trained in European universities.

The text is not only modern but up to date, both in the concepts it presents and in the literature it cites. The bibliography is a good one, and incidentally it lays strong emphasis on American titles. The author is well abreast of the most recent developments in a number of varied special fields, and he sets forth his synthesis with clarity and enthusiasm. RICHARD FOSTER FLINT

Nonmetallic Minerals, 2d ed.; by R. B. Ladoo and W. M. Myers. Pp. xiv, 606; 18 figs. New York, 1951 (McGraw-Hill Book Company, $10.00).—The authors recognize in their introduction that nonmetallic minerals constitute a very heterogeneous group in contrast with the mineral fuels and the metallic minerals. In spite of this heterogeneity, they have assembled in this unique compendium a great storehouse of information.

In alphabetical order (from abrasives, actinolite, and alum minerals to zircon and zirconium minerals) the nonmetallic minerals are described. Normally the following headings are used under each substance: composition, general description, physical properties, occurrence, production, utilization. In appropriate cases, extra sections are included on such subjects as mining and milling practices, marketing shipping and prices, and specifications and tests.

The importance of this book as a standard reference cannot be exaggerated. It is virtually a necessity for engineers and executives interested in the development of large or small nonmetallic deposits. To the teacher it furnishes material for enlivening the study of mineral economics as well as mineral systematics.

HORACE WINCHELL

Tabellen zur optischen Bestimmung der gesteinsbildenden Minerale; by W. E. Tröger. Pp. xi, 147; 2 folded plates. Stuttgart, 1952 (E. Schweizerbart'sche Verlagsbuchhandlung, DM 27.80).—

This book is the successor to Mügge's familiar *Hilfstabellen zur mikroskopischen Mineralbestimmung*. The main table is arranged with ten principal columns showing mineral name, composition, crystallography, physical properties, plastic behavior (i.e., gliding, etc.), optical properties, chemical diagnostics, distinctions from similar minerals, and the ordinary paragenesis of each mineral. The 244 minerals are indexed, and in the supplementary tables they are referred to by their serial numbers in the main table, not by page numbers. Variation diagrams and crystal drawings showing optic orientation occupy pages interleaved with those of the main table, so that the serial number of a mineral may not be the easiest key to its location.

A special feature of the book is the extensive collection of variation diagrams, including 36 previously unpublished ones. Nomograms and charts to facilitate certain computations occupy 9 pages, and several auxiliary determinative tables list the rock-forming minerals according to their densities, dispersions, properties obtainable from interference figures due to cleavage plates, color and pleochroism, and miscellaneous other observations (e.g., pleochroic haloes, minerals in groups determined by magnetic separations, solubilities).

To a few minor features there may be objections, but there can be no doubt of the value of the book as a whole. Students and petrographers will consider it a useful auxiliary tabulation, worthy of a place alongside more comprehensive references.

HORACE WINCHELL

Les Stromatoporoïdes du Dévonien Moyen et Supérieur du Bassin de Dinant, Deuxième Partie; by MARIUS LECOMPTE. Inst. Royal des Sci. Nat. de Belgique, Mem. 117. Pp. 219-359; plates 36-70. Brussels, 1952.—This is the second and concluding volume of Dr. Lecompte's magnificent monograph on Devonian stromatoporoids (see this JOURNAL, vol. 250, p. 841). It completes the description of genera and species and includes an extensive bibliography and index for the entire work. The fulltone plates are impressive.

CARL O. DUNBAR

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Sun, Moon, and Planets; by R. K. Marshall. New York, 1952 (Henry Holt and Company, $2.50).

Laboratory Experiments in College Chemistry; by V. R. Damerell. New York, 1952 (The Macmillan Company, $1.75, paper cover).

Biology and Language; by J. H. Woodger. New York, 1952 (Cambridge University Press, $8.00).

Introductory Mycology; by C. J. Alexopoulos. New York and London, 1952 (John Wiley & Sons, Inc., and Chapman & Hall, Ltd., $7.00).

Europe, 2d ed.; by S. Van Valkenburg, and C. C. Held. New York and London, 1952 (John Wiley & Sons, Inc., and Chapman & Hall, Ltd., $7.50).

Design for A Brain; by W. R. Ashby. New York, 1952 (John Wiley & Sons, Inc., $6.00).

Lillie's Development of the Chick, 3d ed.; revised by H. L. Hamilton, New York, 1952 (Henry Holt and Company, $8.50).

Comets and Meteor Streams; by J. G. Porter. The International Astrophysics Series, Vol. 2. New York, 1952 (John Wiley & Sons, Inc., $5.25).

An Introduction to the Chemistry of the Hydrides; by D. T. Hurd. New York and London, 1952 (John Wiley & Sons, Inc., and Chapman & Hall, Ltd., $5.50).

Geology of the Colony of North Borneo; by Max Reinhard and Eduard Wenk. London, 1951 (His Majesty's Stationery Office, £ 2 12s. 6d).

Textbook of Quantitative Inorganic Analysis, 3d ed.; by I. M. Kolthoff and E. B. Sandell. New York, 1952 (The Macmillan Company, $6.50).

Fundamental Principles of Polymerization — Rubbers, Plastics, and Fibers; by G. F. D'Alelio. New York and London, 1952 (John Wiley & Sons, Inc., and Chapman & Hall, Ltd., $10.00).

Inorganic Chemistry — An Advanced Textbook; by Therald Moeller. New York and London, 1952 (John Wiley & Sons, Inc., and Chapman & Hall, Ltd., $10.00).

Sir Douglas Mawson Anniversary Volume: Contributions to Geology in Honour of Professor Sir Douglas Mawson's 70th Birthday Anniversary Presented by Colleagues, Friends and Pupils; M. F. Glaessner and E. A. Rudd, Editors. Pp. 224; illustrated. Adelaide, South Australia, 1952 (University of Adelaide, 30 shillings (Aust.), paper cover).

Proceedings of the First Ohio Water Clinic, 1952. Ohio State University Engineering Experiment Station Bulletin 147. Columbus, 1952 (Ohio State University, $1.00, paper cover).

Oil and Gas Developments in Kansas During 1951; by W. A. ver Wiebe, J. M. Jewett, E. D. Goebel, and A. L. Hornbaker. Kansas State Geological Survey Bulletin 97. Lawrence, 1952 (University of Kansas).

Finality and Form; by W. S. McCulloch. Springfield, Illinois, 1952 (Charles C. Thomas, Publisher, $3.75).

The Moral Theory of Behavior; by F. R. Barta. Springfield, Illinois, 1952 (Charles C. Thomas, Publisher, $2.00).

Geologia del Distrito Minero de la Higuera Ubicado en la Provincia de Coquimbo; by Jorge Muñoz Cristi. Universidad de Chile Instituto de Geologia Publicacion 1. Santiago, 1950.

North Dakota Geological Survey Circular 5, 2d. revision. Well Data and Tops of Significant Wells. Grand Forks, 1952 (University of North Dakota).

GEOCHEMISTS: ATTENTION

Symposium on Geochemistry in Zürich, 10-15 August 1953, president: Michael Fleischer, local chairman: C. Burri, will be held under the auspices of Section of Inorganic Chemistry of the International Union of Chemistry and will be devoted to two general themes:

1) The problem of organizing and making available geochemical data: Reports by organizations engaged in revision and compilation of existing data of geochemistry, compilation and computation of rock analyses, etc.

2) Geochemical research the world over, with a summary of replies received to questionnaire, and individual reports on current work from various centers.

The scientific sessions will be followed by a one- or two-day field excursion.

A complete program will be sent upon request. Apply to secretary: Prof. T. F. W. Barth, Geologisk Museum, Oslo 45, Norway.

GEOLOGICAL ABSTRACTS

The American Geological Institute, through the good offices of its member societies and the editors of geological journals, is beginning a compilation of geological abstracts. The first issue will cover January to June 1953, and will be circulated to subscribers about July 15. Thereafter the issue will be quarterly scheduled as March 30, June 30, September 30, and December 30, of each year.

The subscription price will not exceed $2.00 per year. So that the editors may anticipate printing requirements, will all geologists interested in subscribing to the new service send a postal card at once to: American Geological Institute, 2101 Constitution Avenue, N. W., Washington 25, D. C. *Do not send any subscription money now!*

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